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### FUEL CELL STACK ASSEMBLY

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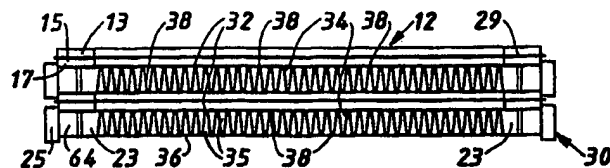
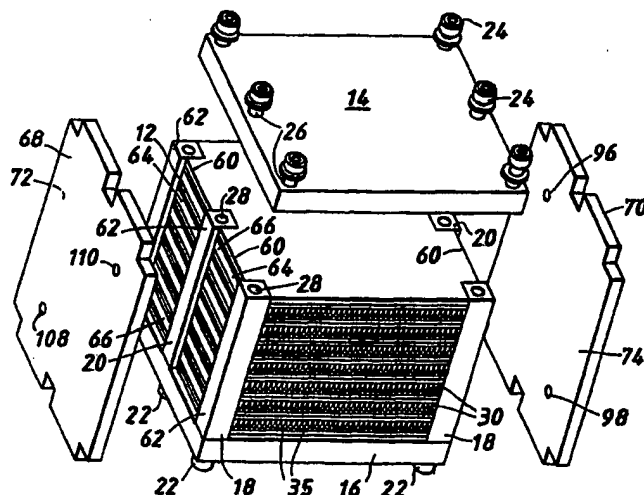
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A fuel cell stack (10) assembly comprises an aligned series of multi-function strata (panels) (30) alternating with and interposed between a mating series of electrochemically active strata (12). In a proton exchange membrane (PEM)-type fuel cell stack, the electrochemically active fuel cell strata include membrane electrode assembly (MEA) strata. The multi-function panels provide structural integrity and electric circuit continuity within the stack. Each multi-function stratum comprises an open spring conductive layer (34), such as an undulate or corrugated layer, sandwiched between a pair of relatively rigid conductive layers (32, 36) that isolate the open spring layer from the reactant gases. The layers of the multi-function stratum together constitute a distributed spring array exerting a compressive force acting in the stack dimension, each open spring layer bearing compressively against the rigid conductive sheets between which it is sandwiched. This distributed spring array facilitates the maintenance of dimensional integrity within the stack, permitting an external manifold to be provided for the supply and exhaust of reactant gases to and from the stack. The spaces provided between the open spring elements serve as conduits for cooling air, so that cooling air may flow over the corrugations to cool the stack. A simple economical frame structure and associated cover plates and separator bars for the fuel cell stack form and enclose separate plena for the supply and exhaust of reactant gases for the fuel cells in the stack.



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## FUEL CELL STACK ASSEMBLY

**FIELD OF THE INVENTION**

The present invention relates to a stack assembly primarily for an electrochemical fuel cell of the proton exchange membrane (PEM) type, and to a multi-function stratum for inclusion in a PEM-type fuel cell stack. The multi-function stratum serves as (i) a heat dissipator; (ii) a compression spring arrangement for maintaining the stack in compression; and (iii) an electrical conductor between successive electrochemically active strata in the stack.

**BACKGROUND**

Electrochemical fuel cells convert fuel and oxidant to direct electric current and reaction product. In electrochemical fuel cells employing hydrogen as the fuel and oxygen as the oxidant, the reaction product is water. Solid polymer fuel cells of the PEM type include a membrane electrode assembly (MEA) layer comprising a solid polymer electrolyte serving as an ion exchange membrane disposed between two electrode layers. The electrode layers typically comprise porous, electrically conductive sheet material and an electrocatalyst at each membrane-electrode interface to promote the desired electrochemical reaction. At the anode, fuel from the fuel supply moves into and through the porous electrode material and is oxidized with the aid of the anode electrocatalyst. The reaction forms cations (typically protons obtained from the hydrogen fuel supply), that migrate through the membrane to the cathode, and electrons that move into an electric circuit that includes a load and is connected to the cathode. At the cathode, the oxidant moves into and through the porous electrode material and reacts with the aid of the cathode

electrocatalyst to form anions. The anions so formed react with the cations arriving through the PEM from the anode to produce a reaction product, typically water. The cathode reaction requires the electric circuit to supply the electrons needed to provide the negative charge for the anions that neutralize the arriving cations and form with the cations the electrically neutral reaction product.

In conventional PEM fuel cells, the MEA is interposed between two substantially fluid-impermeable, electrically conductive plates (sometimes referred to as separator plates) to form a fuel cell unit. The plates serve as current collectors and conductors, provide structural support for the electrode layers, typically include conduits for directing the fuel and oxidant to the anode and cathode layers, respectively, and typically provide means for removing reaction products, typically water, formed during operation of the fuel cell. When reactant channels for the fuel and oxidant are formed in the separator plates, the plates are sometimes referred to as fluid flowfield plates. Since in stacked fuel cell arrangements a given separator plate typically has an anode adjacent the obverse broad surface and a cathode adjacent the reverse broad surface, such plates are sometimes referred to as bipolar plates.

Individual fuel cells are typically electrically interconnected in series in a stacked array between stack end plates (to which terminals for connection to the external electrical load are connected) in order to generate usable electrical power. The dimension through the stack from one terminal end plate to the other is referred to in this specification as the stack dimension. The stack must be retained between the terminal end plates under compression to maintain sealing between MEA and plate subassemblies and to provide adequate electrical conductivity between subassemblies. Conduits must be

provided adjacent the electrode layers for the supply of fuel and oxidant gases respectively; these conduits are typically formed in the separator plates, as mentioned. MEA layers alternate in the stack dimension with separator plates; similarly fuel supply flowpaths alternate in the stack dimension with oxidant supply flowpaths so that the fuel supply is isolated from the oxidant supply. These flowpaths and associated exhaust conduits must also be supplied to remove the spent reactant gases and the reaction product (typically water). In most fuel cells, particularly those of larger dimensions, means such as auxiliary cooling passages for flow of cooling water through the stack must be provided to remove heat from the stack, as the chemical reactions are exothermic.

As mentioned, in such stack arrangements, one broad surface of a given fluid flow field plate, bipolar plate, or separator plate serves as the anode conductor for one cell, and the other broad surface of the plate serves as the cathode conductor for the adjacent cell. Fluid reactant streams are typically supplied to channels in the flowfield plates via internal plena or manifolds formed by aligning openings formed within the plates and MEA layers in the stack. Similarly, fluid exhaust manifolds for spent gases and reaction products are also typically located internally within the stack; suitable apertures in the separator plates and MEA strata are frequently provided for this purpose.

Some types of fuel cell operate at relatively high temperatures. For example, phosphoric acid fuel cells operate at about 200°C. Heat may be readily removed from such cells by air cooling. By contrast, a conventional PEM fuel cell operates at about 80°C. Unless a given PEM-type fuel cell stack is of sufficiently low power (say, lower than about 30 kW) and of sufficiently small dimensions that heat can be dissipated into the environment without special assistance (see Fletcher *et al.* U.S. Patent No. 5,470,671 granted to

Ballard Power Systems Inc. on 28 November 1995 for an example of such small low-power fuel cell stack), some heat dissipation means must be designed into the fuel cell configuration so that the low-grade heat generated from the fuel cell stack during its operation may be removed to maintain the desired working temperature. In conventional PEM fuel cell stack design, because the operating temperature does not differ by much from ambient (say, room) temperature, air cooling has been found to be ineffective. Accordingly, conventional stacks typically also have coolant passageways extending within them for circulating a coolant liquid that absorbs the heat generated by the exothermic fuel cell reaction. The coolant liquid typically flows out of the stack to a heat exchanger and then the re-cooled liquid recycles into the stack. The requirement for such coolant flow necessitates the use of a circulating pump as well as the heat exchanger and coolant flow conduits, thereby adding to the cost, weight and bulk of conventional PEM fuel cell stack and associated assemblies. As PEM fuel cell stacks are otherwise suitable for use in mobile applications such as powering vehicles, bulk and weight should be kept to a minimum.

In some types of fuel cell stack, external manifolds connected to the sides of the stack for providing side-located supply and exhaust plena for the reactant gases may be provided instead of internal plena or manifolds. The use of external manifolds with a fuel cell stack allows reactant and oxidant gases to be fed directly to the sides of the stack and thence to the internal reactant fuel and oxidant gas conduits. Compared to a stack with internal manifolds, a stack with external manifolds has simple manifold interfaces and assembly requirements, which translate into lower manufacturing and assembly costs. External manifolds have been used for molten carbonate fuel cells. However, for a conventional PEM fuel cell stack, such external manifold architecture

cannot maintain adequate sealing along the manifold interface, at least in the case of a relatively large high-power stack. The reason for this problem is that during operation, a PEM fuel cell stack undergoes both thermal expansion throughout and also hydro-expansion of its proton exchange membranes by reason of absorption of water by those membranes; further, compression of the components tends over time to cause component shrinkage in the stack dimension (*i.e.*, as explained previously, along the dimension perpendicular to the broad working surfaces of the stacked MEA layers and the separator plates) of some of the fuel cell components, notably the porous electrode layers and the seals. These expansions, contractions and shrinkages cause the stack as a whole to expand and/or contract in the stack dimension, interfering with conduit alignment, disrupting seals and presenting a serious impediment to the use of external manifolds on such stacks. Sealing is critical in fuel cell stacks; especially important is the need to avoid any co-mingling of fuel and oxidant gases, which at best would reduce the efficiency of the cell, and at worst could cause an explosion. For the foregoing reasons, virtually all commercially manufactured PEM-type fuel cell stacks have used internal manifolding, as will be discussed in further detail below.

Because of the movement over time of PEM fuel cell strata in the stack dimension, in almost all high-power PEM fuel cell stacks currently manufactured heretofore, stack expansion-compensating compression springs are used at one or both ends of the stack to compensate for the expansion and compression of the stack. The compressive force exerted by these springs maintains internal seals between adjacent MEA/plate subassemblies and their associated conduits for fuel, oxidant, and coolant supply, and reaction product disposal, despite the tendency over time for the stack strata (subassemblies) to shrink in the stack dimension, and despite intermittent expansions and



contractions of the stack strata. Such springs also facilitate adequate electrical conductivity between the serially connected strata. Unfortunately, as mentioned above, PEM fuel cell stacks tend not to be stable in the stack dimension; motion along the stack dimension is then propagated to all reactant and oxidant gas delivery plates. Consequently, in accordance with conventional PEM fuel cell stack design, manifolding and associated seals are internally located, since external seal and manifold conduit alignment cannot pursuant to conventional design be properly maintained in the stack dimension. If external manifolding were attempted in such conventional PEM stacks, the continual motion of the plates would tend to break the seals between the edges of the plates and the fixed external manifolds coupled to the stack, thereby rendering unworkable the otherwise desirable external manifolding for high-power fuel cell stacks.

Various specific fuel cell stack design approaches in the prior literature have limited merit within the context of their objectives, but none has resolved the set of problems to which reference is made above. Because of the unique physical and chemical properties of PEM fuel cell stacks, design approaches directed to other types of fuel cell often are not transposable to PEM fuel cell stack design. In the literature relating to commercially manufactured PEM fuel cell stack design, inevitably internal manifolding is utilized.

The following prior patent specifications are illustrative of the state of fuel cell stack technology:

Bette, U.S. Patent No. 5,397,655, granted 14 March 1995, discloses a PEM-type fuel cell stack with resilient spring plates between adjacent cells. Bette does not teach any manifolding of the fuel cell stack. Bette apparently

uses the spring plates to adjust voltage drop; the specification teaches that the voltage drop within the fuel cell stack is "adjustable within wide limits, which is achieved, for instance, by inserting additional, or differently shaped spring plates 10, or other intervening layers" (column 4, line 60ff). There is no disclosure of the use of such spring plates for the purpose of maintaining dimensional stability within the stack dimension, nor any teaching as to how such spring plates could be adapted for use in multiple-function configurations nor in conjunction with an external manifold.

Mattejat, U.S. Patent No. 5,472,801, granted 5 December 1995, discloses a PEM-type fuel cell with intervening contact plates provided with "stamped out contact tongues" (column 6, line 57) that might arguably function as spring plates similar to those of Bette. Mattejat's teaching suffers from the same deficiencies as the Bette teaching mentioned above.

Kothmann, U.S. Patent No. 4,276,355, granted 30 June 1981, discloses an externally manifolded air-cooled fuel cell stack. This stack is for use with a liquid electrolyte-type fuel cell employing phosphoric acid as the electrolyte. Such cells are not susceptible to the same sort of dimensional instability as PEM fuel cell stacks. There is nothing in the Kothmann teaching to suggest that compression occurs, and nothing to suggest the use of compensating springs or the like. Kothmann discloses the use of a solid cooling block between two bipolar plates. The cooling block cannot accommodate the expansion and contraction of fuel cell components. Further, the cooling block is bulky, adding to the weight and volume of the fuel cell stack, and tends to be inefficient for heat dissipation. It would not be expected to be suitable for dissipating low-grade heat generated by medium to high power PEM fuel cells. Nothing in the Kothmann patent suggests that his phosphoric acid fuel cell

design would be suitable for use in a PEM fuel cell stack.

Kumata, U.S. Patent No. 4,508,793, issued 2 April 1985, and Tajima, U.S. Patent No. 5,541,015, granted 30 July 1996, each disclose an externally manifolded phosphoric acid liquid electrolyte air-cooled fuel cell stack, and each is subject to the same deficiencies in teaching as the Kothmann patent.

The specification of Siemens AG German Patent Application Serial No. DE 44 42 285 C1, published 8 February 1996, discloses a stamped metal fuel cell configuration. An intermediate panel is disclosed whose functions include improving mechanical support, transferring electric current and providing a contact surface for air cooling of the stack. Although Siemens teaches that interwoven or tangled wire or wire mesh may be used as the panel material (none of which would have any appreciable springiness), nevertheless the panel may have sufficient spring properties to generate a modest internal thrust force against fuel cell plates. However, the rigid frames of the component fuel cells must remain in contact. These frames determine the stack dimension. Any thermal or hydro expansion has to be accommodated by external springs. This fuel cell stack design uses internal manifolds; there is no discussion of the possibility of external manifolding nor of the need to maintain dimensional stability in the stack dimension to accommodate such possibility.

Baker, U.S. Patent No. 4,169,917, granted 2 October 1979, discloses an air-cooled fuel cell incorporating layers configured as rectangular corrugations and other geometries for use as corrugated layers. Baker does not disclose any dimensional stability problems, nor any use of the corrugated layer or any other layer as a compression spring, nor the use of internal springs

of any sort to maintain dimensional stability. There is no discussion of the manifolding for the fuel cell.

Maru, U.S. Patent No. 4,444,851, granted 24 April 1984, discloses an externally manifolded air-cooled fuel cell stack, but there is no disclosure of means for compensation of dimensional instability in the stack dimension; further, Maru does not disclose that his configuration would be suitable for a PEM-type fuel cell stack. The problem of dimensional alignment within an externally manifolded fuel cell stack is not addressed.

Sasaki, U.S. Patent No. 5,378,247, granted 3 January 1995, discloses a corrugated separator for a molten carbonate-type fuel cell. There is no suggestion that this configuration would be suitable for use in a PEM-type fuel cell. There is no discussion of dimensional instability in the fuel cell stack nor means to maintain dimensional stability, nor of manifolding of this particular type of fuel cell.

Leonida, U.S. Patent No. 5,446,354, granted 14 November 1995, is not directed to fuel cell design at all, but rather to electrolysis cell design. Leonida discloses a metal compression pad interposed between pairs of stacked electrolysis cells in order to compress the cells so as to compensate for dimensional variations and thermal expansion, and to provide electrical connection. Leonida does not teach the use of such pads for use in fuel cell stacks, nor is Leonida concerned with manifolding or heat dissipation.

Other literature disclosing some fuel cell stack structures of interest includes the following:

1. Anahara, R., "Research, Development, and Demonstration of Phosphoric Acid Fuel Cell Systems , (8.3.3.2 Air-Cooling System)" *Fuel Cell Systems*, L. J. Blomen (ed.), Plenum, 1993, pp. 296-297.
2. Gibb, P., et al. "Electrochemical Fuel Cell Stack with Compression Mechanism Extending Through Interior Manifold Headers," U.S. Patent No. 5,484,666, Jan. 16, 1996.
3. Selman, J. R., "Research, Development, and Demonstration of Molten Carbonate Fuel Cell Systems, (9.2.6 Stack Structure & 9.4.1. Stack Configuration and Sealing)" *Fuel Cell Systems*, L. J. Blomen (ed.), Plenum, 1993, pp. 357-359 & pp. 398-399.

## SUMMARY OF THE INVENTION

The invention comprises improvements in fuel cell stack design, primarily for PEM-type fuel cell stacks, including a novel multi-function stratum (panel) for use in such stack, and an external manifolding arrangement suitable for use with such stack.

A fuel cell stack assembly according to the invention (particularly useful for a PEM-type fuel cell stack) in a preferred embodiment includes an aligned series of uniform multi-function strata or panels alternating with and interposed between a mating series of uniform electrochemically active fuel cell strata, which in a PEM-type fuel cell stack are either fuel cell units or membrane electrode assembly (MEA) layers. (Obviously a terminating one of such strata must be provided adjacent the terminal end plate at either end of the stack.) Each stratum is a discrete sub-assembly. Each fuel cell stratum may be of conventional manufacture; such stratum includes the electrode layers, electrocatalytic layers, and polymeric proton exchange membrane electrolytic

layer in the case of an MEA layer-type fuel cell stratum and in the case of a fuel cell unit-type fuel cell stratum includes separators. Each multi-function stratum comprises an interior open spring layer or equivalent sandwiched between a pair of relatively rigid conductive layers. Such rigid conductive layers in an orthogonal stack configuration (*i.e.*, a stack having the overall shape of a rectangular parallelepiped) are generally planar in the form of a thin, flat, parallelepiped, so that the multi-function stratum has the overall shape of a generally flat panel, the interior open spring layer being sandwiched between the rigid conductive layers. The rigid conductive layers need not be rigid in the sense that a desktop, say, is rigid, but should impart sufficient rigidity to the sandwich structure that the multi-function panel maintains its structural integrity within the stack. As will be discussed below, it may in some circumstances in which fuel cell units are used as fuel cell strata be possible to depart from strict alternation of fuel cell strata with multi-function strata and to have two or possibly more fuel cell strata in immediate succession in the stack followed by a multi-function stratum, but such is not normally preferred.

The open spring layer of each multi-function stratum may conveniently be in the form of a corrugated or other undulate sheet. Alternatively, the open spring layer could be formed as a spaced array of fins of identical transverse cross-section shaped to provide the function of a compression spring; that cross-section could for example be S-shaped or undulate. As a further alternative, the open spring layer could be an array of coil springs whose axes are parallel to the stack dimension. As a further alternative, the open spring layer could be manufactured from a single sheet of elastic material subjected to cutting and punching to create an inset array of integrally connected springs.

(In this last embodiment, the cut and punched sheet could function both as one of the rigid layers and as the spring layer.) Alternatively, the open spring

layer could be a corrugated metal mesh. Further suitable structures may be imagined. Not all will be equally convenient to manufacture nor equally effective to provide spring compression, conduct electricity, or dissipate heat.

The common characteristics of all of these alternative choices for the open spring layer are elasticity (springiness), heat and electrical conductivity, and an open structure permitting cooling air to flow through the multi-function stratum and absorb heat from the open spring material, which is conveniently a springy (elastic) metal.

It is of course essential that continuity of the electric circuit in the stack dimension through the strata of the stack be maintained, so choosing a conductive material as that of which the spring layer is made meets that requirement; further, good electrical conductors tend to be good heat conductors and dissipators. Preferably the spring layer is electrically and physically bonded to each of the rigid layers between which it is sandwiched; if for example the spring layer is a continuous undulate sheet, then the apices of the undulations are bonded to the contiguous rigid layers.

The spring layer must be shaped to provide continuous open spaces therethrough so that when the fuel cell stack is operational, heat from the spring layer material (to which heat has been transferred from the fuel cell strata adjacent) may be transferred efficiently to cooling fluid (typically air) passed through the open spaces in the **spring layer**. For manufacturing convenience, the spring layer is preferably uniformly constructed from one airflow end to the other; it is desirably invariant in the airflow dimension, subject to any need to generate some turbulence in the airflow to increase the rate of heat dissipation.

The open spring layer sandwiched between each pair of rigid conductive sheets in a multi-function stratum constitutes a distributed spring exerting a compressive force acting in the stack dimension on the rigid conductive sheets between which it is sandwiched and consequently acting on all of the strata in the stack. The set of such layers in the stack constitutes a distributed spring array that can eliminate the need for a separate compression spring at the end of the stack.

In this specification and the appended claims, the three mutually perpendicular directions and dimensions of interest are for convenience of description and definition named as follows:

- (a) The stack dimension is the dimension extending from one extremity of the fuel cell stack to the other, perpendicular to the layers of the stack and perpendicular to the broad working surfaces of the fuel cell strata. In the appended drawings showing the fuel cell stack, for convenience this dimension is presented as the vertical dimension.
- (b) The airflow dimension is the dimension parallel to the flow of cooling air or other cooling fluid through the multi-function panels.
- (c) The transverse dimension is the dimension from one manifold cover plate (see description below) to the other, perpendicular to the other two dimensions. Where the open spring layer is formed as an undulate layer, this dimension extends from the beginning of the waveform to the end of the waveform of the layer.

In embodiments of the invention in which the fuel cell strata are MEA layers, the outer surfaces of the rigid conductive sheets (*i.e.*, the surfaces that are in contact with adjacent MEA layers in the stack) of each multi-function stratum should be inert to reactant gases (*i.e.*, the fuel and oxidant gases) in the



fuel cell stack. An inert coating or protective layer may be applied to the outer surfaces rigid sheets, or the rigid conductive sheets themselves may be made of material inert to the reactant gases and non-poisonous to the fuel cell MEA layers, such as graphite. The use in fuel cells of certain selected types of fuel-cell compatible stainless steel such as 316L stainless steel has also been proposed in the literature. The rigid conductive layers also serve as protective layers for the spring layer, so that reactant gases do not reach such spring layer to react with it. Suitable protective layers include graphite foil and curable graphite-containing inks or pastes.

The open spring layer, as mentioned, may preferably be an undulate or corrugated sheet. The terms "undulate layer", "undulate sheet", "corrugated sheet" or "corrugated layer" used herein mean any sheet or layer of a suitable degree of springiness having undulations that provide suitable apices for physical and electrical contact with the rigid conductive plates or layers, and which undulations also define air passageways to permit cooling air to flow from one end of the corrugations or undulations to the other (each end being exposed to the ambient air or coupled to a forced air circuit that forces cooling air over the undulations). Such undulate layers do not include, for example, corrugated sheets having a rectangular waveform, because these lack the requisite springiness, and would tend to buckle or crumple rather than flex under load. The physical contact of the corrugated sheet with the protective rigid plates or layers permits heat to flow from fuel cell strata through the rigid plates and thence to the corrugated sheet, which thus serves as a heat exchanger or dissipator to dissipate heat into the cooling air passing over the corrugations. This heat dissipation arrangement thus functions in a manner similar to the operation of a conventional automobile radiator. The corrugated layer must be made of metal or other suitable springy material so that the requisite degree of

compressive force can be applied by the corrugated sheet in the stack dimension to the rigid plates, thereby maintaining an overall compressive force in the stack dimension within the stack. The undulate layer must be both thermally and electrically conductive; thermal conductivity is necessary for adequate heat dissipation, and electrical conductivity is necessary to enable low-resistance current flow through the stack. While a technically acceptable substitute for a conductive springy sheet having continuous corrugations or undulations would be a layer provided with (i) fins or other suitable heat transfer surfaces for heat dissipation (heat transfer to the cooling airflow), (ii) conductive contact surfaces for thermal, physical and electrical contact with adjacent layers, and (iii) springs for applying compressive force in the stack dimension, any such substitute layer is likely to be appreciably more expensive to manufacture and install than a continuous corrugated or undulating sheet or layer, so the latter is preferred.

While the fuel cell stack of the invention has been and will be for the most part described as including planar strata and layers (apart from corrugations and the necessary flowpath structures), it is apparent that other configurations are possible, for example generally parallel curved subassemblies (strata) could be devised in lieu of planar strata. As a practical matter, the rigid sheets of the multi-function panel will usually be planar, as that choice lends design and manufacturing convenience to the implementation of the present invention, in which case the stack dimension is perpendicular to the plane of the multi-function panel sheets, and the stack lends itself to an orthogonal description. But it is possible to construct the fuel cell strata and multi-function panels as themselves undulate overall, or arcuate, or otherwise departing from planar. The concepts described herein using the named dimensions as applied to such planar and orthogonal stack configurations may

be modified to accommodate non-orthogonal stacks or non-planar strata.

Further, while the invention has thus far been described as requiring the use of conductive rigid sheets between which the corrugated sheet (or other suitable equivalent open spring layer) is sandwiched, it is apparent that the entirety of the sheets need not be conductive. What is required is adequate electrical conductivity between adjacent fuel cell strata. As long as the rigid sheets include adequate provision for such electrical conductivity, they need not be uniformly conductive throughout. It is also apparent that any protective coating applied to such sheets must not unacceptably interfere with the electrical conductive path; accordingly, preferably any such protective coating, if applied at all, should be selected to be electrically conductive. If the protective coating or layer is made of material that is conductive, non-poisonous to the MEA layers, and inert to reactant gases (graphite being a suitable choice), then no problem arises, as the entirety of the multi-function stratum will then be both conductive and non-reactive. Otherwise, if the rigid plate is not entirely conductive or a protective layer applied to it is not conductive, some means such as an array of spaced chemically inert conductors extending from or through the protective coating or rigid layer or both could be provided.

There must also be in the fuel cell stack some suitable means for providing a supply of reactant gases to the electrochemically active layers of each fuel cell stratum. In a PEM-type fuel cell stack, fuel gas is supplied to one active layer of a fuel cell stratum and oxidant gas is supplied to the other active layer of each fuel cell stratum. (An "active layer" is one to which fuel or oxidant, as the case may be, is delivered to enable the electrochemical reaction to take place. Such active layer is typically a porous cathode layer or

a porous anode layer.) The gas delivery means may be conveniently integrally formed on the outer surface of the conductive rigid layer of the multi-function panel as a pattern of flowpath channels if the fuel cell stratum is an MEA layer, or the gas delivery means may be formed integrally within the fuel cell stratum if the fuel cell stratum is a fuel cell unit.

In a preferred embodiment, the means for providing fuel gas comprises a configuration of one or (depending upon fuel cell dimensions) preferably two or more meandering fuel channels formed in the outer surface of one of each pair of the protective layers associated with each of said multiple-function panels. A similar set of meandering oxidant channels is formed in the outer surface of the other of each such pair of protective layers. The meandering channels may be of conventional design. By "meandering" is meant that each channel typically has a length appreciably greater than either dimension of the major broad surface of the protective layer, and accordingly is provided with a number of reverse curves to enable the channel to supply gas to a relatively large portion of the MEA porous electrode layer adjacent. The pattern of meandering channels on either surface of the multiple-function panel is designed to be sufficient to provide gas to almost the entirety of the exposed MEA porous electrode layer surface adjacent. The meandering fuel channel pattern or configuration is exposed to an adjacent porous anode layer of an adjacent MEA layer, while the meandering oxidant channel pattern or configuration is exposed to an adjacent porous cathode layer of an adjacent MEA layer. In current conventional fuel cell design, such meandering channels are typically serpentine. The channel walls should be of uniform height and should contact the adjacent membrane electrode assembly throughout the length of the walls, but if all the fuel channels are formed on one side of the multiple-function panel and all the oxidant channels are formed

on the other side, then minor imperfections or leaks in the channel walls will be inconsequential.

Perforce each channel in the fuel supply channel configuration is provided with an inlet fuel port and an outlet fuel port. The inlet fuel port may conveniently communicate with a fuel supply plenum and the outlet fuel port may conveniently communicate with a fuel exhaust plenum. Similarly, each channel in the oxidant supply channel configuration is provided with an inlet oxidant port and an outlet oxidant port, the inlet oxidant port advantageously communicating with an oxidant supply plenum and the outlet oxidant port advantageously communicating with an oxidant exhaust plenum. Each plenum is isolated from every other plenum (except via the reactant flowpaths) by means of walls that may be formed in a manifold external to the various layers within the fuel cell stack. The manifold is provided with conduits, at least one conduit per plenum, for connecting each plenum to a respective associated source of fuel or oxidant gas, or sink of spent fuel or oxidant gas, as the case may be.

The invention comprises a fuel cell stack of the type heretofore described, but it also comprises a multi-function stratum (composite panel) of the type described. Such multi-function stratum is particularly suitable for use as a stratum or panel alternating with MEA layers in a PEM-type fuel cell stack assembly of the type defined above.

Such multi-function strata or panels may each suitably comprise a corrugated metal sheet sandwiched between two flat metal sheets. As mentioned, such multi-function strata serve as both the heat dissipating elements of the stack and the springs to compensate for thermal and hydro

expansion and age contraction of the fuel cells in the stack. The multi-function strata also provide structural support for the porous electrode layers adjacent and serve as current collectors to interconnect all fuel cells in the stack. The multi-function panels form a distributed spring system that force the "floating" (otherwise free to move in the stack dimension) fuel cells and their reactant gas delivery plates into fixed positions. Undesired motion of the fuel cells and their associated plates along the stack dimension is effectively eliminated, making the sealing of external manifolds easy to accomplish, and thus making feasible the use of external manifolds for a high-power PEM-type fuel cell stack.

The associated structure of the fuel cell stack may advantageously include pillars disposed peripherally about the stack and extending in the stack dimension. The terminal plates may be fixed to the pillars and may form with the pillars a structurally sound "cage" or frame for the stack. The pillars thereby provide both structural integrity and mounting surfaces for mounting external manifold cover plates. The fuel cell stack is thus seen to comprise, within the framework of the pillars and terminal plates, an aligned series of repeated combinations of elements, each of which combinations consists in one preferred embodiment of the invention, of an MEA layer, a pair of reactant gas delivery plates, and a multi-function panel and, in a second preferred embodiment of the invention, of an MEA layer and a multi-function panel. These repeated elements are flexible in the stack dimension and are constrained by the solid frame of the stack.

For obvious reasons, the fuel cell stack requires seals to prevent reactant gases from commingling, to prevent such gases from reacting with other materials in the stack (notably the metal in the corrugated layer), etc. The

seals for the stack may include gaskets or sealant-filled channels around the reactant and oxidant flowpath channels, gaskets at the manifold interface with support pillars or other stack side surfaces, spacers inserted between the supply and exhaust plena and the sides of the multi-function strata thereadjacent, and applied sealing cement where required.

It is also an aspect of the invention to use hydrogen as a fuel gas in a fuel cell stack of the type heretofore described that includes a plurality of multi-function panels that are embodiments of the present invention stacked together with the fuel cell units of the fuel cell stack, each multi-function panel being interposed between a unique pair of said fuel cell units. Each multi-function panel includes: (i) a pair of relatively rigid thermally and electrically conductive layers; and (ii) an electrically and thermally conductive elastic open spring layer sandwiched between and in mechanical, thermal and electrical contact with the rigid layers, the open spring layer when the associated multi-function panel is installed in a fuel cell stack providing electrical and thermal conductivity between the rigid layers, providing heat dissipation into the surrounding fluid medium of heat transferred to the multi-function panel from the fuel cells in the stack, and serving as a compression spring exerting on the rigid layers a compressive force generally perpendicular to the panel for providing compressive force within the stack in the stack dimension. Each fuel cell unit in the fuel cell stack includes a membrane electrode assembly (sometimes referred to herein as "MEA" or "MEA assembly" or "MEA sandwich") formed as a "sandwich" having as the two outermost layers of the sandwich an anode electrode comprising porous anode material, and a cathode electrode comprising porous cathode material. The "filling" of the sandwich comprises an electrolytic membrane layer disposed between the two electrodes, an anode electro-catalyst layer disposed between the electrolytic membrane

layer and the anode electrode, and a cathode electro-catalyst layer disposed between the electrolytic membrane layer and the cathode electrode. A fuel cell unit is formed when this MEA sandwich is installed between a first flow-field plate, a selected side of which provides flow channels of a flow field for hydrogen, and a second flow-field plate, a selected side of which provides flow channels of a flow field for a selected oxidant. The selected side of the first plate faces and is in contact with the anode electrode and the selected side of second plate faces and is in contact with the cathode electrode so that the hydrogen flow channels are closed to form a conduit for supplying hydrogen to the membrane electrode assembly and the oxidant flow channels are closed to form a conduit for supplying oxidant to the membrane electrode assembly.

According to another aspect of the invention, hydrogen may be used as a fuel gas in a fuel cell stack that includes a plurality of multi-function panels that are another embodiment of the present invention stacked together with the MEA layers of the fuel cell stack, each multi-function panel being interposed between a unique pair of said MEA layers, the multi-function panels acting as a flow-field-defining structures. In this version of the fuel cell, the membrane electrode assembly, as in the previously described embodiment, is formed as a sandwich as described above, but the two flow-field plates are omitted and the flow fields, channels, and conduits are formed by multi-function panels that have been coated or otherwise made inert to reactant gases present in the fuel cell stack and non-poisonous to the membrane electrode assembly, but are otherwise as described in the preceding paragraph. Flow channels are provided on or in the surfaces of the rigid layers.

It can be seen that the principal difference between the two fuel cell stack embodiments just described is that in the first embodiment described



above, the flow-fields are provided by the separator plates of the fuel cell stratum itself, whereas in the second embodiment the flow-fields are provided by the multi-function panels.

The use of hydrogen as a fuel in fuel cells of the described construction constitutes an advantageous aspect of the invention. Both types of the fuel cell strata described in the preceding paragraphs operate when hydrogen is supplied to the hydrogen conduit, oxygen is supplied to the oxidant conduit, and a circuit that includes a load and is capable of receiving electrons from the anode electrode and supplying electrons to the cathode electrode is connected to the anode electrode and the cathode electrode. In theory, the load could be applied across an individual fuel cell, but in practice a number of such fuel cells are stacked in a fuel cell stack, with the layers of all of the fuel cells being substantially parallel in most conventional fuel cells. The stack is provided with a terminal cathode at one end and a terminal anode at the other, across which terminals the load is connected. When hydrogen and oxygen or other suitable oxidant are supplied to the fuel cells in the stack, then in each fuel cell, hydrogen moves from the hydrogen flow field through the porous anode electrode and is ionized at the anode electro-catalyst of the membrane electrode assembly to yield electrons and hydrogen ions. The electrolytic membrane layer of the membrane electrode assembly is permeable to hydrogen ions (protons), but is not conductive. Hence only the hydrogen ions may migrate through the electrolytic membrane layer. The hydrogen ions after migrating through the electrolytic membrane react with oxygen that has moved from the oxidant flow field through the porous cathode electrode to the cathode electro-catalyst and electrons supplied by the circuit. The reaction product is water. To make up for the loss of electrons provided to the cathode electrode, the circuit receives electrons from the anode electrode. A useful current of

electrons through the load is thereby provided. A fuel cell stack may be formed from two or more of the fuel cells described above in a conventional manner known to those familiar with fuel cell technology and therefore need not be described in detail here.

While the advantages of all of the described aspects of the invention have particular application to PEM-type fuel cell stack design, some of them can be utilized to good effect in other types of fuel cell stack. For example, the multi-function panels could be used in other types of fuel cell stack as heat dissipators, even if they were not required for dimensional stability of the stack to compensate for thermal and hydro expansion or fuel cell shrinkage with age. The efficiency of the overall stack architecture could be advantageous for other types of fuel cell. However, the full benefit of the fuel cell stack variants and multi-function panels discussed herein is expected to be achieved only if the fuel cells are PEM-type fuel cells.

## SUMMARY OF THE DRAWINGS

Figure 1 is a schematic isometric view of an embodiment of a PEM-type fuel cell stack constructed in accordance with the present invention.

Figure 2 is a schematic exploded isometric view of the fuel cell stack of Figure 1.

Figure 3 is a schematic isometric exploded view of a side portion of the fuel cell stack of Figure 2 showing also gaskets suitable for insertion in the space between the cover plate and side posts of the fuel cell stack of Figure 2.

Figure 4 is a schematic front elevation view of the fuel cell stack of

Figure 1.

Figure 5 is a schematic section view of a representative corrugated sheet layer of the fuel cell stack of Figure 1 taken along the line V-V of Figure 4.

Figure 6 is a schematic section view of an embodiment of a fuel flowpath configuration of a representative fuel cell in the stack of Figure 1 taken along the line VI-VI of Figure 4.

Figure 7 is a schematic section view of an embodiment of an oxidant flowpath configuration of a representative fuel cell in the stack of Figure 1 taken along the line VII-VII of Figure 4.

Figure 8 is a schematic section view of an alternative fuel flowpath configuration that may be substituted for that of Figure 6.

Figure 9 is a schematic section view of an alternative oxidant flowpath configuration that may be substituted for that of Figure 7.

Figure 10 is a schematic fragmentary exploded view of a multi-function stratum of the fuel cell stack of Figure 1, showing in greater detail the configuration of the corrugated sheet layer.

Figure 11 is a schematic front elevation view of two strata of the fuel cell stack of Figure 1 showing in greater detail the configuration of the multi-function stratum.

Figure 12 is a schematic exploded fragmentary front elevation view of

a portion of Figure 11, showing the spacer and multi-function stratum arrangement of the fuel cell stack of Figure 1.

Figure 13 (prior art) is a schematic diagram representing the conventional spring-loading of fuel cells in a PEM-type fuel cell stack, as practised prior to the present invention.

Figure 14 is a schematic diagram illustrating the distributed-spring arrangement of corrugated sheets and fuel cells in a fuel cell stack in accordance with the principles of the present invention.

## DETAILED DESCRIPTION

A fuel cell stack 10 constructed in accordance with the principles of the present invention is schematically illustrated in Figure 1 ff. By way of example only, eight fuel cell strata 12 are shown in Figure 1 in stacked arrangement between an upper terminal plate 14 and a lower (base) terminal plate 16 for the fuel cell stack assembly 10. (An actual relatively high-power fuel cell stack might typically have several dozen fuel cells in the stack.) The terminal plates 14, 16 are fixed to corner support pillars or posts 18 and intermediate support pillars or posts 20, all of which pillars 18, 20 rest on the base terminal plate 16. The fixing of the pillars 18 and 20 to the base plate 16 may be conveniently effected by screwing bolts 22 through mating holes (not shown) in base terminal plate 16 and thence into mating threaded holes (not shown) in the bases of pillars 18 and 20. The upper terminal plate 14 may be fixed to the pillars 18 and 20 by means of bolts 24 that penetrate through mating holes 26 in the upper terminal plate 14 and thread into mating threaded receptacle holes 28 in the tops of pillars 18 and 20.

A complete repeating unit of the stack 10 comprises a fuel cell stratum 12 and an adjacent multi-function stratum or panel 30. The structure of the multi-function stratum 30 is more clearly illustrated in Figure 11; see also the exploded view of Figure 10.

Figure 11 illustrates, in schematic vertical sequence, an exemplary pair of consecutive repeating units of the stack, each repeating unit comprising a fuel cell stratum 12 and a multi-function stratum 30. Each fuel cell stratum 12 may be a fuel cell unit of conventional manufacture comprising an upper separator/flow-field plate 13 for fuel gas, an intermediate MEA layer 15, and a lower separator/flow field plate 17 for oxidant gas. Alternatively, each fuel cell stratum 12 may include a discrete MEA layer without separator/flow field plates. Fuel cell strata that are fuel cell units are referred to herein as fuel cell units 12 and fuel cell strata that are MEA layers without separator/flow field plates are referred to herein as MEA layers 12, where it is necessary to distinguish between the two forms of fuel cell strata. If it is not necessary to distinguish between the two forms of fuel cell strata, then they are both referred to as fuel cell strata 12. Both forms of fuel cell strata are conventional.

The multi-function strata 30 each comprise an upper rigid layer or plate 32, an intermediate open spring layer in the form of corrugated layer 34, and a lower rigid layer or plate 36. The three layers 32, 34, 36 may conveniently be made of metal, provided that care is taken to prevent metal poisoning of the MEA layers if the multi-function strata 30 are to be used with MEA layers 12. While some choices of metal are relatively inert, others, such as copper, would be suitable for electrical and thermal conductivity, but would contaminate the MEA layers 12. So when such fuel cell poisoning materials as copper are

chosen for the material of which the rigid layers 32, 36 are made, it is necessary to interpose an inert medium between the metal and the neighbouring MEA layers 12. Such inert medium can be a graphite coating, for example, applied to the metal, preferably after roughening the metal surface by sandblasting or the like to improve the adhesion of the coating to the rigid layer.

A protective coating found suitable for use in fuel cells is a castable graphite tooling material that is similar to monolithic graphite in a manufacturing environment, but has increased strength. One such material is sold as Hyper Cast™ Graphite by Hyper Industries of Bonita, California. Such graphite is sold in a paste form for ease of application. It will cure through a catalyzing process. The curing can take place in several steps at both ambient temperature or somewhat elevated temperatures (40°C - 110°C). If the material is sintered at a high temperature, around 700°C, few if any residual organic or inorganic contaminants will be left (leading to a final coating composition of close to 99% carbon). Alternatively, the metal (say) sheets forming rigid layers 32, 36 could be coated with a graphite paint to form a solid graphite coating over the metal. Alternatively, a separate protective layer such as a graphite foil sheet could be interposed between each rigid layer 32, 36 and the neighbouring MEA layer 12.

If the fuel cell strata are MEA layers 12, then it is possible to form the requisite reactant gas flowfield on the outer surface of each rigid layer 32, 36 so that such layer does double duty, both bearing the walls defining the flowfield structure, and forming a portion of the multi-function sandwich. The castable graphite mentioned in the preceding paragraph can be used to form the flowfield walls on planar layers 32, 36, or the walls may be molded in the

layers 32, 36 prior to coating. Other manufacturing alternatives are possible.

The corrugated sheet layer 34 functions as an electrical conductor, as a heat dissipator, and as a spring. The corrugated layer 34 is most easily manufactured if the corrugations are uniform in both the airflow and transverse dimensions, but there may be particular reasons to provide non-uniform corrugations in either or both dimensions, *e.g.* for generation of air turbulence in the interest of enhancing heat transfer to the cooling air flow. The apices 38 of the corrugated layer 34 make electrical and physical contact with the respective rigid plates 32, 36 adjacent the apices of the corrugated layer 34. The air spaces formed by the corrugations of layer 34 constitute cooling passages 35 for permitting cooling air to flow over the corrugations of the layer 34, thereby resulting in heat transfer from the stack 10 to the cooling air. The cooling air flow can be from the front of the stack 10 to the back (as seen in Figure 1) or *vice versa*, and may be augmented by fans or the like. Spacer bars 64 made of rubber or similar resilient sealing material seal the multi-function panels 30 from the reactant gas plena of the fuel stack, to be described below.

For purposes of optimizing the spring performance of the multi-functional strata 30, each of the apices of the corrugated layer 34 is preferably welded or soldered to the plate 32 or 36 respectively with which such apex of the corrugated layer 34 comes into contact. This can be accomplished by prefabrication of each multi-function stratum 30, for example by providing a layer of solder on the inner surfaces of sheets 32, 36, placing the corrugated layer 34 therebetween, and placing the assembly thus formed into an oven, permitting the solder to melt and form the connections, and then permitting the assembly to cool so that the liquid solder connections solidify, leaving the corrugated layer 34 firmly electrically and conductively bonded between the

upper and lower rigid plates 32, 36.

In the embodiment illustrated in Figure 1, there is a multi-function stratum 30 between each consecutive pair of fuel cell strata 12. However, it is conceivable that in some fuel cell stack designs in which fuel cell strata are fuel cell units 12, the fuel cell units 12 would be thin enough and the fuel cells sufficiently dimensionally stable that two or more fuel cell units 12 could be placed in the stack in immediate contact with one another to form an fuel cell unit subset, between which subsets the multi-function strata 30 might be interposed. This optional arrangement would be expected to work successfully only if the expansion and contraction over time of the fuel cell units are slight and only if the seals provided in the assembly are flexible. Experiments with two fuel cell units per repeated fuel cell unit subset have been successful, but the safer design for most PEM-type fuel cell stacks is expected to be one providing a multi-function stratum between each consecutive pair of fuel cell units.

It is necessary for the reactant gases in the stack assembly of Figure 1 to be independently fed to the respective porous electrode layers of the fuel cell strata 12. Accordingly, each fuel cell stratum 12 is designed so that inlet and outlet ports 90, 94, 104, 106 (Figures 6 and 7) for the reactant flowpaths provided in the fuel cell strata 12 communicate with associated discrete plenum chambers 76, 78, 80 and 82. Each plenum chamber 76, 78, 80 and 82 has a substantially continuous inner boundary surface formed by the side edges 60 of the fuel cell strata 12 and side surfaces 66 of spacer bars 64 (Figures 2, 5, 11 and 12), the side surfaces 66 being aligned with the side edges 60 of the fuel cell strata 12. It will be noted that the side edges 60 of the fuel cell strata 12 are inset from the outer side surfaces 62 of the pillars 18 and 20. The spacer



bars 64 interposed between successive fuel cell strata 12 occupy the entire space between any two adjacent corner and intermediate pillars 18, 20 and between any two consecutive fuel cell strata 12, so as to completely seal off the multi-function panels 30 from the plenum chambers 76, 78, 80 and 82.

As a result of the foregoing configuration, when side cover plates 68, 70 are assembled onto the sides of the fuel stack assembly 10, a gap is left between the inset outer side surfaces 66 of spacer bars 64 and side edges 60 fuel cell strata 12, on the one hand, and the interior surfaces 72, 74 respectively of the side cover plates 68, 70, on the other hand, thereby forming reactant gas plenum chambers 76, 78, 80, 82 respectively. Plenum chambers 76, 78 can be seen to lie within a left-hand manifold arrangement on the left side of the fuel cell stack 10 (as seen in Figures 2, 5, 6, 7) and plenum chambers 80, 82 can be seen to lie within a right-hand manifold arrangement on the right side of the fuel cell stack 10.

Bearing in mind that one of the reactant gases is typically hydrogen, which has a tendency to permeate materials and to escape easily if there is any leak, it is important that adequate sealing be provided for the fuel cell stack 10. It is thus important that the plenum chambers 76, 78, 80, 82 be completely sealed off from one another (apart from the flowpaths interconnecting supply and exhaust plenum chambers for a given reactant gas) and from the ambient environment of the fuel cell stack. Typically fuel cell strata are manufactured as discrete composites provided with peripheral margin portions that are made of material that facilitates sealing. The somewhat resilient sealed margins 29 (Figure 11) of each fuel cell stratum 12 would be expected to provide an adequate seal around the contacting portions of the corner and intermediate posts 18, 20. The spacer bars 64 are preferably formed of resilient material

such as rubber inert to reactant gases, and are preferably made slightly oversized relative to the dimensions of the rigid units of the fuel cell stack 10, so that they are under compression between adjacent intermediate and corner pillars 18, 20 and between consecutive fuel cell strata 12, thereby maintaining a tight seal between the side edges of the multi-function panels 30 and the plenum chambers 76 through 82.

Figures 11 and 12 illustrate the spacer bars 64 inserted into cavities 27 (Figure 12) at the ends of the multi-function strata 30. For convenience, the spacer bars 64 may be provided with oversize outer end caps 25. The interior dimensions of cavity 27 are preferably slightly smaller than the dimensions of the mating spacer bars 64 so as to facilitate a tight seal, but note that there is normally a positive pressure drop between the outer and inner surfaces of spacer bars 64 (the outer surfaces of spacer bars 64 being under pressure from the reactant gases), so that this pressure drop tends also to maintain the spacer bars 64 in place and to force the inner surfaces of the cap portion 25 of the spacer bars into close contact with the adjacent surfaces of the fuel cell strata 12.

If desired, spaces 23 outside the boundaries of open spring panels 34 may be filled with a resilient latex sealing compound deposited as a viscous paste. Preferably, the spacer bars 64 are glued in place within cavities 27 by means of an epoxy glue, or the like.

To complete the sealing of the plenum chambers 76 through 82, gaskets such as the gaskets 71, 73 illustrated in Figure 3 are preferably provided between the side cover plates 68, 70 and the neighbouring pillars 18, 20 against which they are mounted. Mating recesses 75, 77 to receive gaskets 71, 73 may,

if desired, be provided in the inner surface 74 of side plate 70 (and a similar arrangement would, of course, be devised for cover plate 68). Sealing compound may be applied along the gasket surfaces as required in order to augment the seal. Gaskets 71, 73 may be made of an inert material such as rubber, resistant to reactant gases, or they may simply take the form of seals such as silicone sealing strips applied as a viscous liquid to the inner surfaces of the cover plate 68 and 70 and then permitted to solidify. Note that ports 96, 98 are within the boundary of the recesses 75, 77 and mating gaskets 71, 73; this is, of course, essential in order that the ports 96, 98 communicate properly with the plena 80, 82 within the respective sealed-off areas thus bounded.

The mounting arrangement for the cover plates 68, 70 is not critical; no specific mounting means is illustrated in the schematic drawings, but, for example, threaded receptacles (not shown) could be provided along the side edges 62 of pillars 18 and 20, mating holes (not shown) could be provided in the cover plates 68 and 70, and bolts (not shown) could be passed through the mating holes in the cover plate 68 and 70 and threaded into the threaded receptacles (not shown) in the associated pillars 18, 20.

Four plenum chambers 76, 78, 80, 82 having been provided by the fuel cell stack assembly thus far described, it remains to describe the use of these plenum chambers to provide supply and exit passages for the reactant gases.

The specific flowpath embodiments illustrated in Figures 6 and 7 will now be described. First referring to Figure 6, the fuel inlet plenum is the plenum chamber 76 communicating with fuel inlet ports 90 of the flow field 92 in flow field panel 89 illustrated in Figure 6. Flow field 92 comprises a pair of discrete fuel flowpaths 93, 95 running from the inlet ports 90 to

corresponding outlet ports 94. The meandering flowpaths 93, 95 of flow field 92 are serpentine in character so as to provide fuel gas to the active working surface of the underlying (or overlying) porous electrode layer of the associated fuel cell stratum 12. For the embodiment of Figure 6, the plenum chamber 78 constitutes the exhaust plenum for exhaustion of the spent fuel gas. Since the plenum chambers 76 and 78 cannot function without connection to an external source and sink respectively of fuel gas, a fuel inlet port 108 and a fuel outlet port 110 are provided in end cover plate 68 for coupling to an external source (not shown) and sink (not shown) respectively of fuel gas. For this purpose, any suitable coupling element may be provided at each of the ports 108, 110 for coupling to externally mounted tubing (not shown) for connection to the source and sink respectively of the fuel gas.

A similar such arrangement is made for the oxidant gases. Figure 7 illustrates a representative set of serpentine oxidant flowpaths 103, 105, 107, 109, 111, 113 constituting a meandering flowpath arrangement generally indicated as 100 in the associated oxidant flowpath panel 102. An exemplary six flowpaths are illustrated that are provided with a set of inlet ports 104 communicating with supply plenum chamber 80 and a set of outlet ports 106 communicating with exhaust plenum chamber 82. Again, the plenum chambers 80, 82 are provided with a supply port 96 and an exhaust port 98 respectively (Figure 2) in end cover plate 70 for attachment via suitable couplings (not shown) to tubing (not shown) providing a supply and a sink respectively of oxidant gas to the fuel cell stack.

In the flowplates 89, 102, auxiliary sealing cement or the like may be applied in more critical areas if need be. For example, the flowpath configurations of Figures 6 and 7 include disconnected spaces 91, 101

respectively into which epoxy cement or other suitable sealant may be injected.

Various flowpath arrangements can be devised by the designer to suit individual fuel stack designs. The choice of flowpaths will depend in part upon the intended power output, the choice of fuel and oxidant gases, the supply pressure and port size for each gas, the area of the substrate to be covered, the height of the boundary walls for the flowpath, the degree of porosity of the porous electrode layer, the surface texture of the flow channels, and other parameters influencing the pressure drop, flow velocity and Reynold number of the reactant and oxidant gases. Generally speaking, having regard to the respective molecular weights and densities, each fuel flowpath will usually be appreciably longer than each oxidant flowpath; this implies that the number of discrete flowpaths per layer will be higher for the oxidant than for the fuel.

Three principal flowpath layouts are possible, as follows:

- 1) Each fuel flowpath may both enter and exit on the same side of the stack and each oxidant flowpath may enter and exit on the opposite side of the stack. Or,
- 2) the fuel flowpath may enter on one side of the stack and exit on the other side, the oxidant flowpath entering on the fuel path exit side and exiting on the fuel path entrance side. Or
- 3) as the final option, both flowpaths may begin on one side of the stack and both may exit on the opposite side of the stack.

There are various advantages and disadvantages associated with each of the foregoing flowpath design options. For example, if the stack is placed on its side (relative to the orientation shown in Figure 1) such that the exit ports are as a consequence located along the lowermost fuel cell stack surface, then

the third option mentioned above would be optimal for drainage of any surplus water out of the fuel cell stack. (If the stack is designed properly and operating normally, all water should evaporate and be carried off with the effluent spent gases, but sometimes there can be accumulations of liquid water that have to be dealt with.) If the fuel enters and leaves on one side of the stack and the oxidant enters and leaves on the other side of the stack, then it is easier to isolate fuel and oxidant gases from one another so that leaks permitting the two gases to combine outside the fuel cell will be less likely; for this safety reason, the first option mentioned above would be preferred (that is the option embodied in Figures 6 and 7). Finally, the second option, in which the fuel and oxidant flowpaths tend to be oriented overall in roughly opposite directions, has been found to be the most chemically efficient arrangement. So depending upon the priority of importance of the factors mentioned above and possibly others, the designer will select a flowpath design that best meets design criteria and priorities.

By way of further example, Figures 8 and 9 illustrate optional fuel and oxidant flowpath configurations respectively that implement the second design option mentioned above. In Figure 8, fuel flow field panel 51 is provided with two meandering fuel flowpaths 47, 49 running from fuel flowpath entry ports 53, 55 to fuel flowpath exit ports 57, 59. Again a serpentine flowpath arrangement is maintained so that the adjacent porous electrode layer (not shown in Figure 8) next to the flowpaths 47, 49 may be maximally exposed to fuel gas. By arranging the location of fuel flowpath exit ports 57, 59 on the opposite side of the flow field of Figure 8 from the side on which fuel path entry ports 53, 55 are located, it is possible to select (as discussed below) the oxidant fuel path to flow in roughly the opposite direction, thereby achieving the objective of the second design option mentioned above. Note that with the

configuration of Figure 8, it is necessary to re-assign the plenum chamber functions relative to the assignment of Figure 6; accordingly, plenum chamber 76 serves as a fuel supply plenum chamber communicating with the inlet ports 53, 55 of the fuel flowpaths, and plenum chamber 82 serves as a spent fuel exhaust plenum chamber communicating with the exit ports 57, 59 for the fuel flowpaths.

Turning to Figure 9, six serpentine oxidant flowpaths (unlabelled) are illustrated proceeding from oxidant flowpath entry ports 63 through respective individual flowpaths thence to oxidant flowpath exit ports 65. Note that the inlet ports 63 for the oxidant flowpaths are on the opposite side of the fuel stack 10 from the inlet ports 53, 55 for the fuel flowpaths, and equally the outlet ports for fuel (57, 59) and oxidant (65) flowpaths respectively again are on opposite sides of the fuel stack 10, thereby enabling the objective of the second design option mentioned above to be achieved. For this purpose, plenum chamber 80 now serves as the oxidant supply plenum, and plenum chamber 78 serves as the spent oxidant exhaust plenum. The appropriate revised connections of the plenum chambers 76 through 82 will be made to external sources and sinks of fuel and oxidant gases.

The choice of inlet and outlet ports for the flowpaths of Figures 8 and 9 are arbitrary and could be reversed. So ports 57, 59 (Figure 8) could serve as fuel inlet ports and ports 53, 55 as fuel exhaust ports; similarly inlet and outlet ports 63, 65 could be reversed in Figure 9. If such reversals were made, of course the plenum chamber assignments for plenum chambers 76 through 82 would have to be reallocated. Note that such reversal of inlet and outlet port selection is feasible only if the flow channels are of uniform cross-section from end to end. If the flow channels are designed to be tapered, then inlet and

outlet ports cannot be interchanged.

Recall that in conventional PEM-type fuel cell stacks, MEA layers and separator plates are stacked together in a stack that does not include any constituent elements resembling the corrugated layers 34 interposed between successive fuel cell strata 12 in stack 10. In conventional stack assemblies, a compression spring is mounted between one terminal end plate of the stack and the nearest separator plate (or other rigid plate such as a special bearing plate) at one end of the stack, so that expansion or contraction of the fuel cell stack layers can be accommodated by corresponding variations in the extent of compression of the compression spring. The ideal internal pressures within the fuel cell stack can be of the order of 3 bars or higher; the spring stiffness chosen must provide adequate compression over the range of operating conditions of the stack. The spring stiffness chosen should not be so high as to raise the internal pressure above the ideal when the spring is under the maximum compression provided by the operating conditions of the stack. In other words, the spring stiffness must provide a suitable compressive force to maintain the internal pressure within the ideal internal pressure range regardless of whether the spring is relatively compressed, due to, say, hydro expansion, or is relatively uncompressed, due to, say, expected MEA layer shrinkage over time. This previously known spring arrangement is illustrated schematically in Figure 13, which shows a stack of fuel cells 40 of a representative PEM-type fuel cell stack. The fuel cells 40 are spaced from upper end terminal plate 44 of the fuel cell stack 42 to accommodate a spring 46 that maintains the stack in compression between upper end terminal plate 44 and lower end terminal plate 43 notwithstanding continual compression and expansion of the fuel cells 40 in the stack 42. (In actual practice, a plurality of springs 46 spaced from one another over the area of upper terminal plate 44



would typically be provided, rather than the single spring 46 shown in the interest of simplifying the schematic diagram.)

By contrast, in accordance with the fuel stack assembly of the present invention, the multi-function strata 30 schematically illustrated in Figure 14 together provide a distributed-spring arrangement throughout the entire fuel stack 10, so that compression and expansion of fuel cell strata 12 are accommodated locally by variations in the extent of compression. The strata 30 must always be under some compression in order to assure alignment and help avoid leakage. The result is that there is no tendency of any individual fuel cell stratum 12 to move along the stack dimension within the fuel cell stack 10. If a given fuel cell stratum (say) 12 expands or contracts, the extent of compression of the associated adjacent multi-function strata 30 changes to compensate for such expansion or contraction of the fuel cell strata 12. The entire assembly of fuel cell strata 12 and multi-function strata 30 are mounted under compression between terminal plates 14 and 16. The initial compression is chosen to be sufficient to compensate for expected stack shrinkage over the lifetime of the stack 10.

In the normal state of affairs, spring 46 (Figure 13) in the conventional design would be under a compression load tending to force together the fuel cells 40 in the stack dimension. Equally, each individual spring layer 56 in the distributed-spring arrangement according to the invention would always be under slight compression, such that the overall compressive load provided by the entirety of the springs 56 of Figure 14 would be roughly equal to the single compressive load exerted by spring 46 of Figure 13 (assuming comparable age, materials, dimensions, power capacity and operating conditions of the fuel cell stacks being compared).

The expected thermal expansion of fuel cell components can be calculated given expected temperature variations, once the coefficients of thermal expansion of the critical materials are ascertained. (The coefficients of thermal expansion are known for virtually all critical materials that may be used in the fuel cell stack; the critical materials are those such as any metals that do expand and contract appreciably with temperature variations. Materials that do not appreciably expand and contract with temperature variations, such as the polymeric electrolytes in PEM fuel cells, can be ignored.) Note that the fuel cell stack frame will expand and contract with temperature changes, and its dimensional variation has to be taken into account also. The expected range of hydro expansion of the proton exchange membrane layer is also known from previous work in fuel cell design and testing, and in any case is best ascertained empirically. Given the calculated total expected expansion of the stack and the ideal internal pressure to be applied to the stack (which will vary with stack dimensions, materials chosen, etc.), the ideal stiffness of the compression

$$K = \frac{pA}{L + \Delta L}$$

spring,  $K$ , can thus be calculated by

where  $p$  is the ideal internal pressure of the stack,  $A$  is the cross-sectional area of the stack perpendicular to the stack dimension,  $L$  is the minimum compression of the compression spring, and  $\Delta L$  is the expected change in stack length (in the stack dimension) due to expected net thermal and hydro expansion and age-induced shrinkage. Generally,  $\Delta L$  is small relative to  $L$ .

Note that in each multi-function stratum, the spring could be either only

the corrugated conductive sheet 34 or equivalent, or instead (and preferably) it is the welded assembly 30 of the corrugated conductive sheet (or equivalent) 34 and the two rigid conductive sheets 32, 36 bonded to the corrugated layer 34. The latter is a preferred structure because of its superior stiffness and strength.

The collective effect of all multi-function strata 30 in the stack 10 is equivalent to the effect of the single spring or spring combination 46 that is normally used at the end of a conventional stack 42 (Figure 13). The multi-function strata 30 collectively have a combined spring stiffness equal to the ideal stiffness  $K$  given by the above equation, which would be the stiffness of the single spring 46 at the end of an equivalent conventional stack 42. Having calculated or determined total required spring stiffness  $K$  for the stack 10 as a whole, the next step is to calculate the required stiffness  $k_i$  for each stratum 30

$$\frac{1}{K} = \frac{1}{k_1} + \dots + \frac{1}{k_n}$$

based upon the series spring formula:

where  $n$  is the number of multi-function strata in the stack, and  $k_n$  is the stiffness of the  $n$ th multi-function stratum.

Since the strata are all identical,  $k_i = k_j = k_n$ . For  $n$  identical strata, the required stiffness  $k$  of any given multi-function stratum can accordingly be calculated by:

$$k = nK$$

This required stiffness could be accomplished by suitably selecting the

properties of the multi-function panels 30. Selectable parameters include the thickness of the corrugated conductive sheet 34 or equivalent, the thickness (or height) of the stratum 30, the material of which layers 32, 34, 36 are made, and the shape and period of the waveform of layer 34. Given a set of panel parameters for multi-function panel 30, the deformation of the panel 30 under various loads can be calculated using a finite element analysis computer model. The calculated result may be used to guide the designer to fine-tune the foregoing parameters to make the stratum stiffer or softer until the target stiffness is achieved. Since design criteria and objectives will vary considerably from one fuel cell stack design to another, an empirical approach is recommended.

Note that the fuel stack assembly described herein embodies not only an electrochemically effective design that provides cooling efficiency and mechanical stability, but it also embodies a design that can be realized with a relatively small number of constituent elements, many of which perform more than one function. The several functions of the multi-function stratum has already been discussed above - each such stratum contributes to the distributed spring design and maintains dimensional stability in the stack direction. The multi-function stratum also provides electrical contact between fuel cell units and provides heat-dissipating surfaces and cooling passages through the stack. Other constituent elements of the stack equally contribute to economy of manufacture. For example, the pillar/spacer/cover plate design described permits the pillars to serve as strong rigid structural elements extending longitudinally throughout the stack; these pillars also serve to define, with the inset spacer bars and marginal edges of the MEA layer, the spaces inset from the manifold cover that constitute the supply and exhaust plena for fuel and oxidant gases. The space bars function not only as fillers and to the structural

integrity of the stack but also serve as sealing units, since they are selected to be of a resilient material that can expand or contract to fill completely the space between adjacent pillars and alongside adjacent multi-function strata.

Note that the described embodiment also provides for easy maintenance in the event of a failure of an MEA layer or other unit of the stack. It not infrequently happens that in a fuel cell stack, some electrochemical problem arises - for example, an MEA layer fails to function properly. In such cases, with conventional PEM-type fuel cells, it is often necessary to disassemble the entire fuel cell stack and remove and replace the defective unit in order to cure the problem. By contrast, with the design of the present invention, it is possible simply to remove the manifold cover plates, block the fuel and oxidant inlet and outlet passages of the defective unit, and provide a conductive bridge to pass current from the sound unit on one side of the defective unit to the sound unit lying on the other side of the defective unit, thereby providing electrical continuity throughout the fuel stack assembly. The result is that if, for example, a fuel stack assembly includes 120 fuel cells arranged in series, and one defective unit is bypassed according to the foregoing procedure, there will be a loss of 1 fuel cell, representing a power capacity decline of the 120-unit stack of something less than 1%, which is tolerable for many fuel cell applications.

Note also that the fuel stack design described herein lends itself to modular construction; modular stacks of, say, twenty fuel cells each could be manufactured and placed end to end in a series configuration to bring the total number of cells in a composite stack to a desired target number (say, 120 fuel cells). The terminal plates 14, 16 of fuel stack 10 illustrated would, of course, have to be suitably modified for convenient end-to-end physical and electrical

contact for use in such modular arrangement.

While temperature differentials between interior stack temperatures and ambient temperature will normally promote a sufficient flow of air through the stack 10 to dissipate the low-grade heat produced during stack operation, nevertheless, for high power applications, it may be desirable to provide one or more fans to blow cooling air through the stack 10, or devise a turbocharger-type arrangement that would force air through the stack 10 in a closed conduit communicating with the cooling passages 35 provided by the corrugated spring layers 34. Further, the structural characteristics of the open spring layers 34 may be varied to increase heat dissipation. For example, the layers 34 may be provided with punched openings and/or a rough finish for improved heat dissipation capability.

Hydrogen may be used as a fuel gas in the fuel cell stack 10 illustrated in Figure 1 and described above. If the fuel cell strata are fuel cell units 12, then conduits for supplying hydrogen to the anode electrode layers and oxidant to the cathode electrode layers are provided by the fuel cell units 12. Alternatively, if the fuel cell strata are MEA layers 12, then when the fuel cell stack 10 is assembled, the hydrogen and oxidant flow channels provided by the rigid plates 32, 36 are thereby closed to form conduits for supplying hydrogen to the anode electrode layers and oxidant to the cathode electrode layers, respectively, of the MEA layers. If we focus on a single fuel cell stratum 12 and consider the rest of the fuel cell stack 10 to be part of an external circuit (the rest of which is not shown) that includes a load and is capable of receiving electrons from the anode electrode layer of that fuel cell stratum 12 and supplying electrons to the cathode electrode layer of that fuel cell stratum 12, then when hydrogen is supplied to the hydrogen conduit adjacent the anode

electrode layer of that fuel cell stratum 12 and oxygen is supplied to the oxidant conduit adjacent the cathode electrode layer of that fuel cell stratum 12, hydrogen moves from the hydrogen flow field through the anode electrode layer and is ionized at the electro-catalyst between the anode electrode layer and the electrolytic membrane layer to yield electrons and hydrogen ions. The hydrogen ions migrate through the electrolytic membrane layer to react with oxygen that has moved from oxidant flow field through the cathode electrode layer to the electro-catalyst layer between the cathode electrode layer and the electrolytic membrane layer and electrons supplied by the external circuit to form water. To make up for the electrons provided to the cathode electrode layer the external circuit receives electrons from the anode electrode layer. A useful current of electrons through the load is thereby provided.

Further equivalents, variants, modifications, and improvements of the fuel cell stack assembly and multi-function stratum described herein will readily occur to those skilled in the technology. The scope of the invention is as defined in the appended claims.

What is claimed is:

1. A multi-function panel for a fuel cell stack for interposition between electrochemically active strata in such stack, comprising
  - (a) a pair of relatively rigid thermally and electrically conductive layers; and
  - (b) an electrically and thermally conductive elastic open spring layer sandwiched between and in mechanical, thermal and electrical contact with the rigid layers;the open spring layer when the multi-function panel is installed in a fuel cell stack
  - (i) providing electrical and thermal conductivity between the rigid layers,
  - (ii) providing heat dissipation into the surrounding fluid medium of heat transferred to the multi-function panel from the electrochemically active strata in the stack, and
  - (iii) serving as a compression spring exerting on the rigid layers a compressive force generally perpendicular to the panel for providing compressive force within the stack in the stack dimension.
2. A multi-function panel as defined in claim 1, wherein the rigid layers are planar.
3. A multi-function panel as defined in claim 1 or 2, wherein the open spring layer is made of metal.
4. A multi-function panel as defined in any of the preceding claims,



wherein the open spring layer is of undulate configuration.

5. A multi-function panel as defined in claim 4, wherein the undulations of the undulate layer are regular and uniform.
6. A multi-function panel as defined in claim 4 or 5, wherein apices of the undulate layer are bonded to the rigid layers.
7. A multi-function panel as defined in any of the preceding claims, sealed at each transverse end thereof.
8. A multi-function panel as defined in any of the preceding claims, wherein the stiffness of the open spring layer is the value of  $k$  in the equation

$$k = nK$$

where  $n$  is the number of multi-function strata in the stack, and  $K$  is the total combined stiffness of the open spring layers of the  $n$  multi-

$$K = \frac{pA}{\Delta L}$$

function strata in the stack, conforming to the value  $K$  in the equation where  $p$  is a selected ideal internal pressure of the stack,  $A$  is the cross-sectional area of the layers of the stack perpendicular to the stack dimension, and  $\Delta L$  is the expected change in stack length (in the stack dimension) due to expected net thermal and hydro expansion and age-induced shrinkage of the stack.

9. A multi-function panel as defined in any of the preceding claims, open at both airflow ends to cooling fluid flow therethrough.
10. A multi-function panel as defined in any of claims 1 - 9 for a PEM-type fuel cell stack, wherein the electrochemically active strata are fuel cell units.
11. A PEM-type fuel cell stack comprising a series of stacked fuel cell units and an interposed series of multi-function panels each interposed between selected associated consecutive fuel cell unit pairs throughout the stack, each said multi-function panel characterized as defined in claim 10.
12. A fuel cell stack as defined in claim 11, wherein the multi-function panels alternate with the fuel cell units.
13. A multi-function panel as defined in any of claims 1 - 9 for a PEM-type fuel cell stack, wherein the electrochemically active strata are MEA layers.
14. A multi-function panel as defined in claim 13, wherein at least the outer surface of each of the rigid conductive layers is made of material that is (i) inert to reactant gases present in the fuel cell stack, and (ii) non-poisonous to the electrochemically active strata.
15. A multi-function panel as defined in claim 13, wherein the rigid layers are made of metal with a coating or protective layer on their exterior surfaces that is (i) inert to reactant gases present in the fuel cell stack, and (ii) non-poisonous to the electrochemically active strata.
16. A multi-function panel as defined in claim 13, wherein the rigid layers are made of graphite.

17. A multi-function panel as defined in any of claims 11 - 16, wherein at least one of the rigid conductive layers carries on its outer surface flow channels configured to provide a reactant gas flow field thereon.

18. A multi-function panel as defined in any of claims 11 to 16, wherein each of the rigid conductive layers carries on its outer surface flow channels configured to provide a reactant gas flow field thereon, one said rigid conductive layer thereby providing a fuel gas flow field, and the other said rigid conductive layer thereby providing an oxidant gas flow field.

19. A multi-function panel as defined in claim 17 or 18, wherein the walls of the flow channels are integral with the rigid conductive layer on which they are carried.

20. A PEM-type fuel cell stack comprising a series of stacked MEA layers and an interposed series of multi-function panels each interposed between selected associated consecutive MEA pairs throughout the stack, the multi-function panels alternating with the MEA layers, each said multi-function panel characterized as defined in any of claims 11 - 19, wherein the interior of each said multi-function panel is isolated from the MEA layers.

21. A fuel cell stack as defined in claim 20, additionally comprising supply and exhaust plena for the reactant gases, said plena

- (i) being mutually isolated from one another and from the multi-function panels;
- (ii) being located at the ends of the stack in the transverse dimension of the stack;
- (iii) extending in the stack direction between the extremities of the

MEA layers;

(iv) being aligned with associated ports accessing the flow fields of the MEA layers; and

(v) being respectively connectable to external sources or sinks of reactant gases;

thereby serving to supply reactant gases to all the MEA layers in the stack and to exhaust spent reactant gases from all the MEA layers in the stack.

22. A fuel cell stack assembly suitable for use in a proton exchange membrane (PEM)-type fuel cell stack, comprising a stack of aligned uniform multi-function strata alternating with and interposed between a mating series of aligned uniform MEA layers, each said multi-function stratum comprising an interior undulate conductive sheet sandwiched between an associated pair of generally planar rigid conductive sheets, each said rigid conductive sheet provided with means for rendering the outer surfaces of said rigid conductive sheets relatively inert to reactant gases present in the fuel cell stack and non-poisonous to the electrochemically active strata, each said undulate conductive sheet constituting a spring exerting a compressive force acting in the stack dimension on an associated pair of said rigid conductive sheets between which such corrugated conductive sheet is sandwiched, the spaces provided between corrugations in the corrugated metal sheets being exposed to cooling air and serving as conduits for cooling air during operation of the fuel cell stack, the corrugated conductive sheets together constituting a distributed spring arrangement within the stack for maintaining the stack in internal compression in the stack dimension, said fuel cell stack assembly further including means for providing electrical conduction through the MEA layers and multi-function strata from one end of the stack through to the other, means for providing a

supply of fuel gas to one porous electrode layer of each said MEA layers, and means for providing a supply of oxidant gas to the other porous electrode layer of each said MEA layers.

23. A fuel cell stack assembly as defined in claim 22, wherein the rigid conductive sheets are made of a relatively inert metal selected for compatibility with materials and reactant gases present in the fuel cell stack.

24. A fuel stack assembly as defined in claim 22 or 23, wherein the means for providing fuel gas comprises a flow field configuration of one or more meandering fuel flow channels formed in the outer surface of one of each pair of the protective layers associated with each of said multi-function strata, said meandering fuel flow channel configuration being exposed to an adjacent porous anode layer of an adjacent one of said MEA layers, the meandering fuel flow channel configuration being selected so that most of the porous anode layer surface is in contact with fuel gas provided in said meandering fuel flow channel configuration when the fuel cell stack is operating; and wherein the means for providing oxidant gas comprises a flow field configuration of one or more meandering oxidant flow channels formed in the outer surface of the other of each pair of the protective layers associated with each of said multi-function strata, said meandering oxidant flow channel configuration being exposed to an adjacent porous cathode layer of an adjacent one of said MEA layers, the meandering oxidant flow channel configuration being selected so that most of the porous cathode layer surface is in contact with oxidant gas provided in said meandering oxidant flow channel configuration when the fuel cell stack is operating.

25. A fuel cell stack assembly as defined in claim 24, wherein each flow

channel in the fuel supply flow channel configuration is provided with an inlet fuel port and an outlet fuel port, the inlet fuel ports communicating with a fuel supply plenum and the outlet fuel ports communicating with a fuel exhaust plenum; and wherein each flow channel in the oxidant supply flow channel configuration is provided with an inlet oxidant port and an outlet oxidant port, the inlet oxidant ports communicating with an oxidant supply plenum and the outlet oxidant ports communicating with an oxidant exhaust plenum.

26. A fuel cell stack assembly as defined in claim 25, wherein the fuel supply plenum is connected to the fuel exhaust plenum by the fuel flow channels and the oxidant supply plenum is connected to the oxidant exhaust plenum by the oxidant flow channels, but the plena are otherwise isolated from one other, the plena being provided with conduits, at least one conduit per plenum, for connecting each said plenum to a respective associated external source of fuel or oxidant gas or associated external sink of spent fuel or oxidant gas.

27. A fuel cell stack assembly as defined in claim 26, wherein the plena are formed as peripherally inset plenum chambers extending from one end of the fuel cell stack assembly to the opposite end of the fuel cell stack assembly in the stack dimension, each said plenum chamber being isolated from the other said plenum chambers by interposed impermeable barriers.

28. A fuel cell stack assembly as defined in claim 27, wherein the barriers include frame pillars for the stack extending from one end of the stack to the other in the stack dimension, and the plena are otherwise bounded by cover plates at the transverse sides of the stack, end plates at the ends of the stack in the stack dimension, transverse side edges of the MEA layers, and spacer bars

sealing the transverse ends of the multi-function strata, said spacer bars being interposed between MEA layers at the transverse side edges of the MEA layers.

29. A fuel cell stack assembly as defined in claim 28, wherein the transverse side edges of the MEA layers are aligned with the transverse side edges of the spacer bars.

30. A fuel cell stack assembly as defined in claim 29, wherein the pillars provide structural strength and dimensional integrity for the fuel stack assembly, the pillars extending peripherally transversely outward from the MEA layers and multi-function strata so as to provide therebetween said plenum chambers.

31. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack connectable via an anode terminal and a cathode terminal to an external load, each said fuel cell being provided with:

(i) two flow-field plates, one side of one plate providing flow channels of a flow field for hydrogen and one side of the other plate providing flow channels of a flow field for a selected oxidant; and

(ii) a membrane electrode assembly having a porous anode electrode, a porous cathode electrode, an electrolytic membrane layer disposed between the two electrodes, an anode electro-catalyst layer disposed between the electrolytic membrane layer and the anode electrode, and a cathode electro-catalyst layer disposed between the electrolytic membrane layer and the cathode electrode;

each said membrane electrode assembly being installed in the stack between

two successive ones of said flow-field plates so that the side of the flow-field plate providing flow channels of a flow field for hydrogen faces and is in contact with the anode side of the membrane electrode assembly, whilst the side of the flow-field plate providing flow channels of a flow field for oxidant faces and is in contact with the cathode side of the membrane electrode assembly, so that the hydrogen flow channels are closed to form a conduit for supplying hydrogen to the membrane electrode assembly and the oxidant flow channels are closed to form a conduit for supplying oxidant to the membrane electrode assembly; and

the fuel cells being stacked in sequence, the anode electrode of the fuel cell at one extremity of the stack being electrically connected to the anode terminal, the cathode electrode of the fuel cell at the other extremity of the stack being electrically connected to the cathode terminal, and the anode electrode of each of the other fuel cells in the stack being electrically connected to the cathode electrode of the next adjacent fuel cell;

characterized in that

(a) a plurality of multi-function panels are stacked together with the fuel cells, each multi-function panel being interposed between a unique pair of said fuel cells, each said multi-function panel including:

(i) a pair of relatively rigid thermally and electrically conductive layers;  
and

(ii) an electrically and thermally conductive elastic open spring layer sandwiched between and in mechanical, thermal and electrical contact



with the rigid layers;

the open spring layer when the associated multi-function panel is installed in a fuel cell stack providing electrical and thermal conductivity between the rigid layers, providing heat dissipation into the surrounding fluid medium of heat transferred to the multi-function panel from the electrochemically active strata in the stack, and serving as a compression spring exerting on the rigid layers a compressive force generally perpendicular to the panel for providing compressive force within the stack in the stack dimension; and

and further characterized in that

(b) when the anode terminal and cathode terminal are electrically connected through an external load and for each fuel cell hydrogen is supplied to the hydrogen conduit and oxygen is supplied to the oxidant conduit, then in each fuel cell hydrogen moves from the hydrogen flow field through the anode electrode and is ionized at the anode electro-catalyst layer to yield electrons and hydrogen ions, the hydrogen ions migrate through the electrolytic membrane layer to react with oxygen that has moved from the oxidant flow field through the cathode to the cathode electro-catalyst layer and with electrons that have moved from the anode electrode electrically connected to the cathode electrode, thereby to form water as a reaction product, and a useful current of electrons is thereby produced through the load.

32. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack as defined in claim 31, wherein the multi-function panels alternate with the fuel cells.

33. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack

connectable via an anode terminal and a cathode terminal to an external load, each said fuel cell being provided with:

- (i) two flow-field plates, one side of one plate providing flow channels of a flow field for hydrogen and one side of the other plate providing flow channels of a flow field for a selected oxidant; and
- (ii) a membrane electrode assembly having a porous anode electrode, a porous cathode electrode, an electrolytic membrane layer disposed between the two electrodes, an anode electro-catalyst layer disposed between the electrolytic membrane layer and the anode electrode, and a cathode electro-catalyst layer disposed between the electrolytic membrane layer and the cathode electrode;

each said membrane electrode assembly being installed in the stack between two successive ones of said flow-field plates so that the side of the flow-field plate providing flow channels of a flow field for hydrogen faces and is in contact with the anode side of the membrane electrode assembly, whilst the side of the flow-field plate providing flow channels of a flow field for oxidant faces and is in contact with the cathode side of the membrane electrode assembly, so that the hydrogen flow channels are closed to form a conduit for supplying hydrogen to the membrane electrode assembly and the oxidant flow channels are closed to form a conduit for supplying oxidant to the membrane electrode assembly; and

the fuel cells being stacked in sequence, the anode electrode of the fuel cell at one extremity of the stack being electrically connected to the anode terminal, the cathode electrode of the fuel cell at the other extremity of the stack being

electrically connected to the cathode terminal, and the anode electrode of each of the other fuel cells in the stack being electrically connected to the cathode electrode of the next adjacent fuel cell;

characterized in that

(a) each flow-field plate constitutes an end transverse surface of an associated discrete multi-function panel including:

- (i) a pair of relatively rigid thermally and electrically conductive layers; and
- (ii) an electrically and thermally conductive elastic open spring layer sandwiched between and in mechanical, thermal and electrical contact with the rigid layers;

the open spring layer when the associated multi-function panel is installed in a fuel cell stack providing electrical and thermal conductivity between the rigid layers, providing heat dissipation into the surrounding fluid medium of heat transferred to the multi-function panel from the electrochemically active strata in the stack, and serving as a compression spring exerting on the rigid layers a compressive force generally perpendicular to the panel for providing compressive force within the stack in the stack dimension; and

the interior of the multi-function panel being isolated from each membrane electrode assembly;

and further characterized in that

(b) when the anode terminal and cathode terminal are electrically connected through an external load and for each fuel cell hydrogen is supplied to the hydrogen conduit and oxygen is supplied to the oxidant conduit, then in each fuel cell hydrogen moves from the hydrogen flow field through the anode electrode and is ionized at the anode electro-catalyst layer to yield electrons and hydrogen ions, the hydrogen ions migrate through the electrolytic membrane layer to react with oxygen that has moved from the oxidant flow field through the cathode to the cathode electro-catalyst layer and with electrons that have moved from the anode electrode electrically connected to the cathode electrode, thereby to form water as a reaction product, and a useful current of electrons is thereby produced through the load.

34. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack as defined in claim 33, wherein at least the outer surface of each of the rigid layers is made of material that is (i) inert to reactant gases present in the fuel cell stack, and (ii) non-poisonous to each membrane electrode assembly.

35. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack as defined in claim 33, wherein the rigid layers are made of metal with a coating or protective layer on their exterior surfaces that is (i) inert to reactant gases present in the fuel cell stack, and (ii) non-poisonous to each membrane electrode assembly.

36. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack as defined in claim 33, wherein the rigid layers are made of graphite.

37. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack as

defined in any of claims 33 - 36, wherein at least one of the rigid layers carries on its outer surface flow channels configured to provide a reactant gas flow field thereon.

38. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack as defined in any of claims 33 - 36, wherein each of the rigid conductive layers carries on its outer surface flow channels configured to provide a reactant gas flow field thereon, one said rigid conductive layer thereby providing a fuel gas flow field, and the other said rigid conductive layer thereby providing an oxidant gas flow field.

39. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack as defined in claim 37 or 38, wherein the walls of the flow channels are integral with the rigid conductive layer on which they are carried.

40. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack as defined in any of claims 31 to 39, wherein the rigid layers of the multi-function panels are substantially planar.

41. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack as defined in any of claims 31 to 40, wherein the open spring layer of each multi-function panel is made of metal.

42. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack as defined in any of claims 31 to 41, wherein the open spring layer of each multi-function panel is of undulate configuration.

43. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack as

defined in claim 42, wherein the undulations of the undulate layer of each multi-function panel is regular and uniform.

44. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack as defined in claim 42 or 43, wherein apices of the undulate layer of each multi-function panel are bonded to the rigid layers.

45. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack as defined in any of claims 31 to 44, wherein each multi-function panel is sealed at each transverse end thereof.

46. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack as defined in any of claims 31 to 45, wherein the stiffness of the open spring layer of each multi-function panel is the value of  $k$  in the equation

$$k = nK$$

where  $n$  is the number of multi-function panels in the stack, and  $K$  is the total combined stiffness of the open spring layers of the  $n$  multi-

$$K = \frac{pA}{L + \Delta L}$$

function panels in the stack, conforming to the value  $K$  in the equation where  $p$  is a selected ideal internal pressure of the stack,  $A$  is the cross-sectional area of the layers of the stack perpendicular to the stack dimension,  $L$  is the minimum compression of the compression spring, and  $\Delta L$  is the expected change in stack length (in the stack dimension) due to expected net thermal and hydro expansion and age-induced

shrinkage of the stack.

47. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack as defined in any of claims 31 to 46, wherein each multi-function panel is open at both airflow ends to cooling fluid flow therethrough.

48. The use of hydrogen as a fuel gas in fuel cells in a fuel cell stack as defined in any of claims 31 to 47, additionally comprising supply and exhaust plena for the reactant gases, said plena

(i) being mutually isolated from one another and from the multi-function panels;

(ii) being located at the ends of the stack in the transverse dimension of the stack;

(iii) extending in the stack direction between the extremities of the fuel cells;

(iv) being aligned with associated ports accessing the flow fields of the fuel cells; and

(v) being respectively connectable to external sources or sinks of reactant gases;

thereby serving to supply reactant gases to all the fuel cells in the stack and to exhaust spent reactant gases from all the fuel cells in the stack.

49. The use of hydrogen as a fuel gas in a proton exchange membrane (PEM)-type fuel cell stack connectable via an anode terminal and a cathode

terminal to an external load comprising

a stack of aligned uniform multi-function strata alternating with and interposed between a mating series of aligned uniform membrane electrode assemblies,

each membrane electrode assembly having a porous anode electrode, a porous cathode electrode, an electrolytic membrane layer disposed between the two electrodes, an anode electro-catalyst layer disposed between the electrolytic membrane layer and the anode electrode, and a cathode electro-catalyst layer disposed between the electrolytic membrane layer and the cathode electrode, the membrane electrode assemblies being stacked in sequence, the anode electrode of the membrane electrode assembly at one extremity of the stack being electrically connected to the anode terminal, the cathode electrode of the membrane electrode assembly at the other extremity of the stack being electrically connected to the cathode terminal, and the anode electrode of each of the other fuel cells in the stack being electrically connected to the cathode electrode of the next adjacent fuel cell,

each said multi-function stratum comprising an interior undulate conductive sheet sandwiched between an associated pair of generally planar rigid conductive sheets,

each said rigid conductive sheet provided with means for rendering the outer surfaces of said rigid conductive sheets relatively inert to reactant gases present in the fuel cell stack and non-poisonous to the electrochemically active strata,

each said undulate conductive sheet constituting a spring exerting a



compressive force acting in the stack dimension on an associated pair of said rigid conductive sheets between which such corrugated conductive sheet is sandwiched, the spaces provided between corrugations in the corrugated metal sheets being exposed to cooling air and serving as conduits for cooling air during operation of the fuel cell stack, the corrugated conductive sheets together constituting a distributed spring arrangement within the stack for maintaining the stack in internal compression in the stack dimension,

said fuel cell stack further including

means for providing a supply of fuel gas to the anode electrode of each said membrane electrode assembly, and

means for providing a supply of oxidant gas to the cathode electrode of each said membrane electrode assembly,

so that when the anode terminal and cathode terminal are electrically connected through an external load and hydrogen is supplied to the membrane electrode assemblies by the fuel gas providing means and oxygen is supplied to the membrane electrode assemblies by the oxidant gas providing means, then in each membrane electrode assembly hydrogen supplied to the anode electrode moves through the anode electrode and is ionized at the anode electro-catalyst layer to yield electrons and hydrogen ions, the hydrogen ions migrate through the electrolytic membrane layer to react with oxygen supplied to the cathode electrode that has moved to the cathode electro-catalyst layer and with electrons that have moved from the anode electrode electrically connected to the cathode electrode, thereby to form water as a reaction product, and a useful

current of electrons is thereby produced through the load.

50. The use of hydrogen as a fuel gas in a proton exchange membrane (PEM)-type fuel cell stack as defined in claim 49, wherein the rigid conductive sheets are made of a relatively inert metal selected for compatibility with materials and reactant gases present in the fuel cell stack.

51. The use of hydrogen as a fuel gas in a proton exchange membrane (PEM)-type fuel cell stack as defined in claim 49 or 50, wherein the means for providing fuel gas comprises a flow field configuration of one or more meandering fuel flow channels formed in the outer surface of one of each pair of the protective layers associated with each of said multi-function strata, said meandering fuel flow channel configuration being exposed to an adjacent porous anode layer of an adjacent one of said membrane electrode assemblies, the meandering fuel flow channel configuration being selected so that most of the porous anode layer surface is in contact with fuel gas provided in said meandering fuel flow channel configuration when the fuel cell stack is operating; and wherein the means for providing oxidant gas comprises a flow field configuration of one or more meandering oxidant flow channels formed in the outer surface of the other of each pair of the protective layers associated with each of said multi-function strata, said meandering oxidant flow channel configuration being exposed to an adjacent porous cathode layer of an adjacent one of said membrane electrode assemblies, the meandering oxidant flow channel configuration being selected so that most of the porous cathode layer surface is in contact with oxidant gas provided in said meandering oxidant flow channel configuration when the fuel cell stack is operating.

52. The use of hydrogen as a fuel gas in a proton exchange membrane

(PEM)-type fuel cell stack as defined in claim 51, wherein each flow channel in the fuel supply flow channel configuration is provided with an inlet fuel port and an outlet fuel port, the inlet fuel ports communicating with a fuel supply plenum and the outlet fuel ports communicating with a fuel exhaust plenum; and wherein each flow channel in the oxidant supply flow channel configuration is provided with an inlet oxidant port and an outlet oxidant port, the inlet oxidant ports communicating with an oxidant supply plenum and the outlet oxidant ports communicating with an oxidant exhaust plenum.

53. The use of hydrogen as a fuel gas in a proton exchange membrane (PEM)-type fuel cell stack as defined in claim 52, wherein the fuel supply plenum is connected to the fuel exhaust plenum by the fuel flow channels and the oxidant supply plenum is connected to the oxidant exhaust plenum by the oxidant flow channels, but the plena are otherwise isolated from one other, the plena being provided with conduits, at least one conduit per plenum, for connecting each said plenum to a respective associated external source of fuel or oxidant gas or associated external sink of spent fuel or oxidant gas.

54. The use of hydrogen as a fuel gas in a proton exchange membrane (PEM)-type fuel cell stack as defined in claim 53, wherein the plena are formed as peripherally inset plenum chambers extending from one end of the fuel cell stack assembly to the opposite end of the fuel cell stack assembly in the stack dimension, each said plenum chamber being isolated from the other said plenum chambers by interposed impermeable barriers.

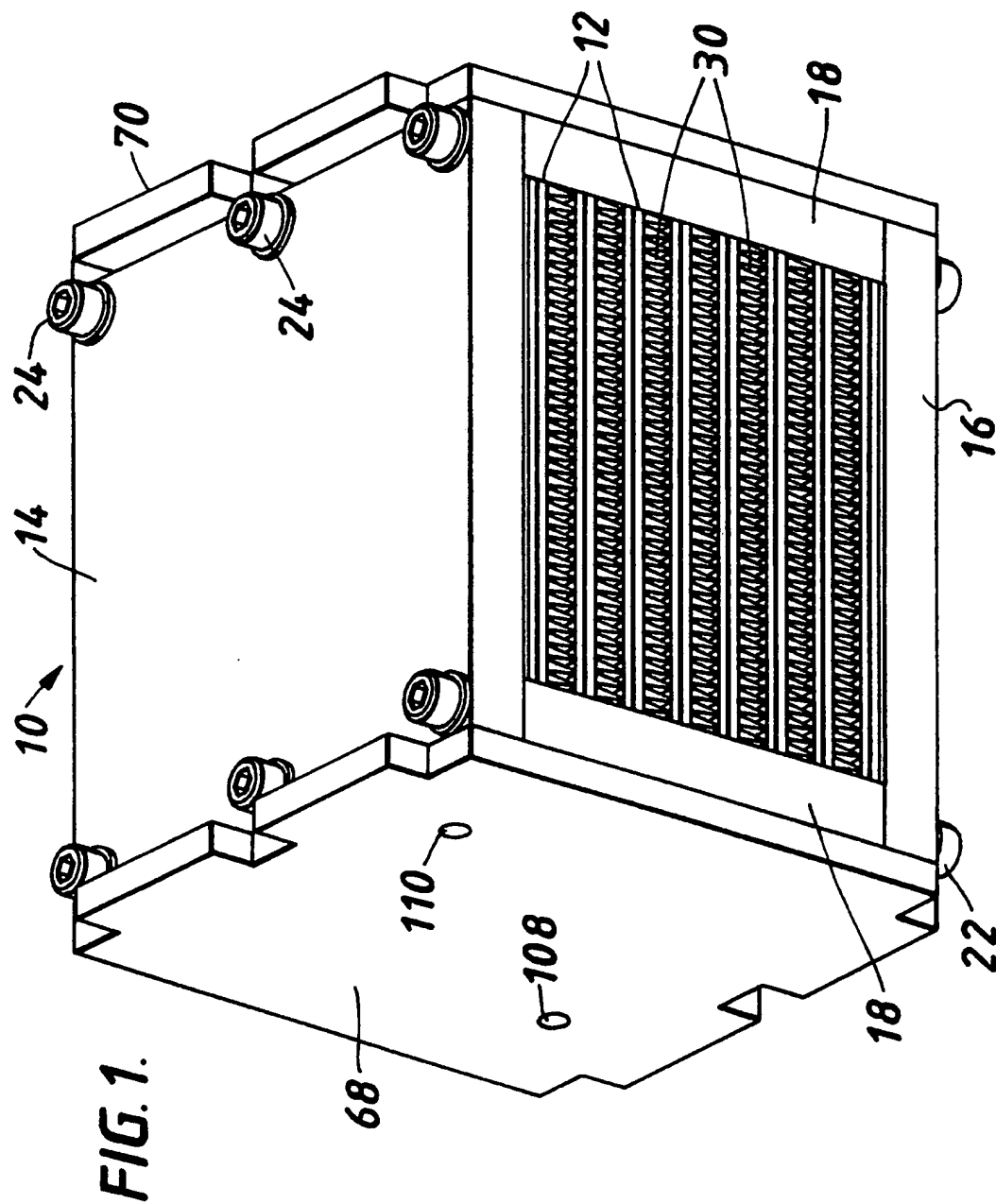
55. The use of hydrogen as a fuel gas in a proton exchange membrane (PEM)-type fuel cell stack as defined in claim 54, wherein the barriers include frame pillars for the stack extending from one end of the stack to the other in the stack dimension, and the plena are otherwise bounded by cover plates at the

transverse sides of the stack, end plates at the ends of the stack in the stack dimension, transverse side edges of the membrane electrode assemblies, and spacer bars sealing the transverse ends of the multi-function strata, said spacer bars being interposed between membrane electrode assemblies at the transverse side edges of the membrane electrode assemblies.

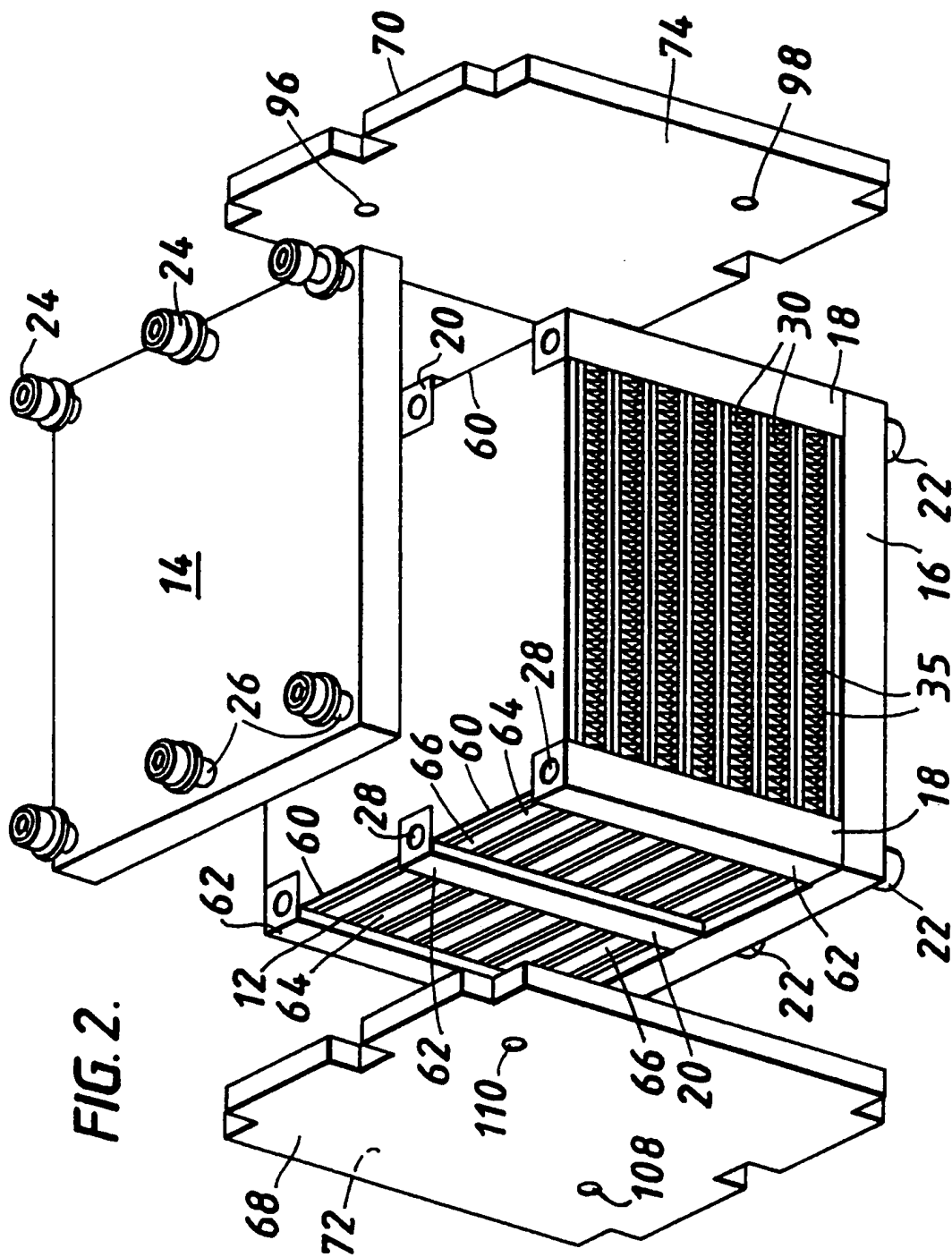
56. The use of hydrogen as a fuel gas in a proton exchange membrane (PEM)-type fuel cell stack as defined in claim 55, wherein the transverse side edges of the membrane electrode assemblies are aligned with the transverse side edges of the spacer bars.

57. The use of hydrogen as a fuel gas in a proton exchange membrane (PEM)-type fuel cell stack as defined in claim 56, wherein the pillars provide structural strength and dimensional integrity for the fuel stack assembly, the pillars extending peripherally transversely outward from the membrane electrode assemblies and multi-function strata so as to provide therebetween said plenum chambers.

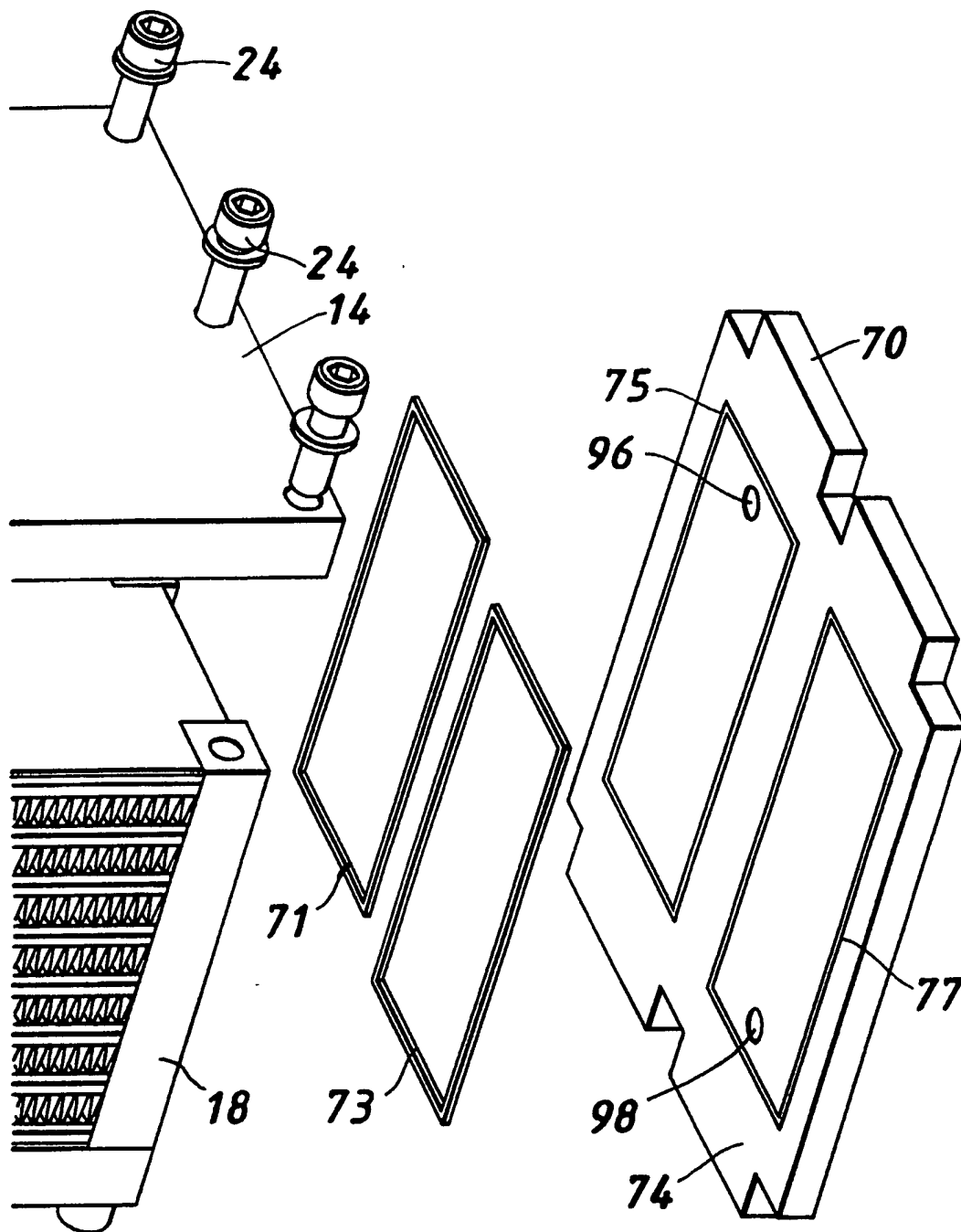
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2/8



3/8  
FIG.3.



4/8

FIG. 4

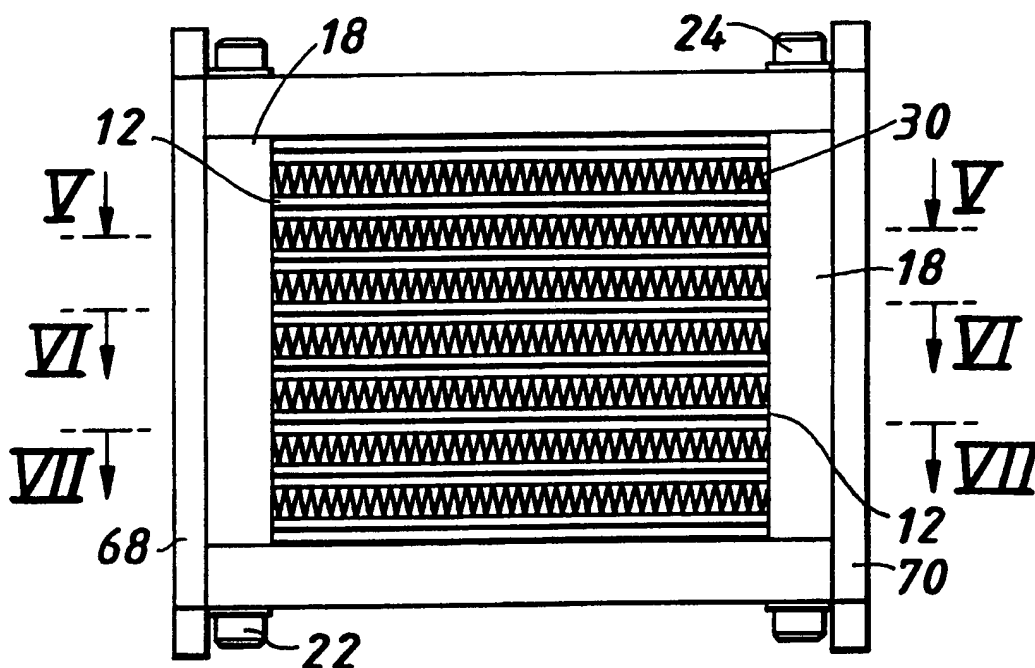
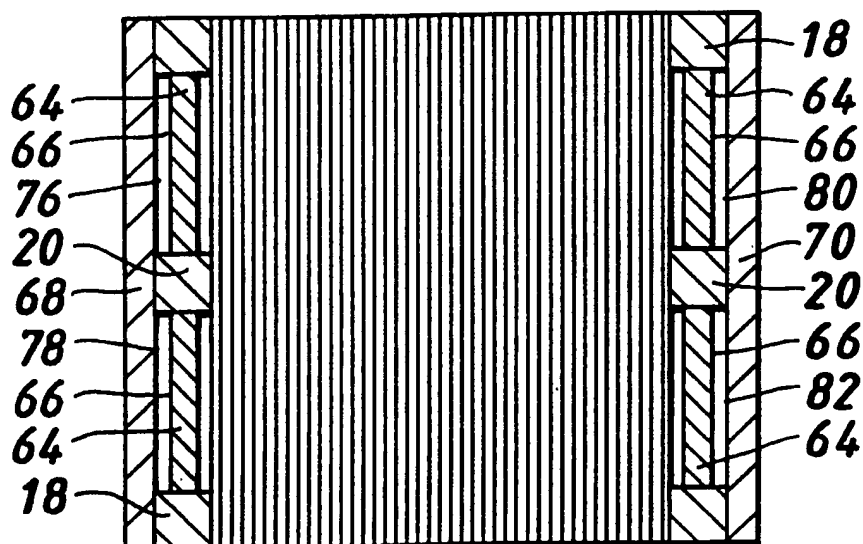


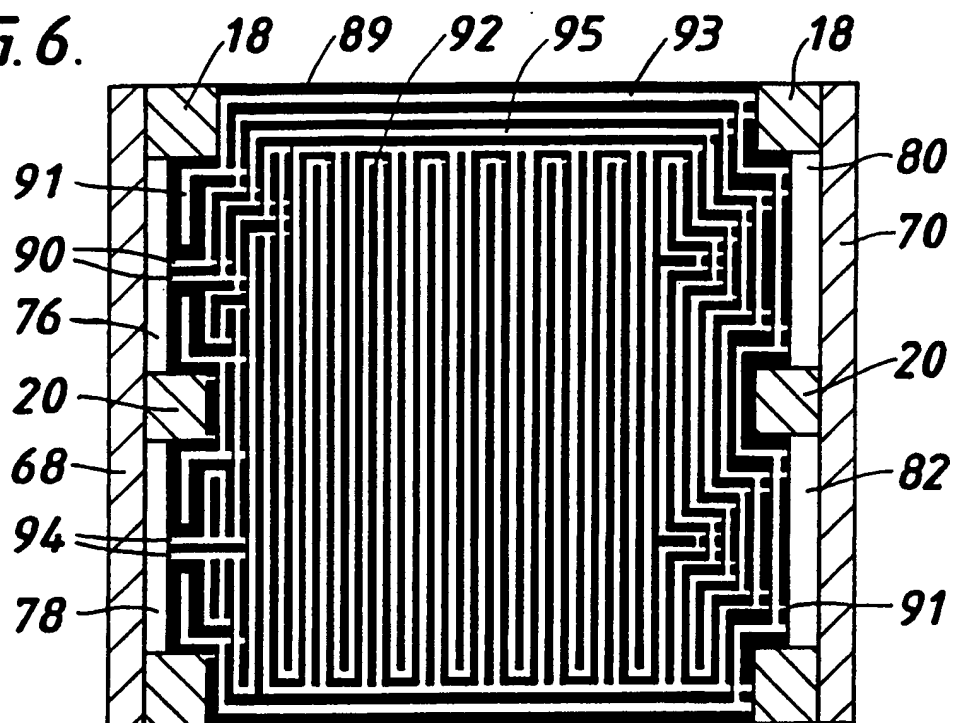
FIG. 5.



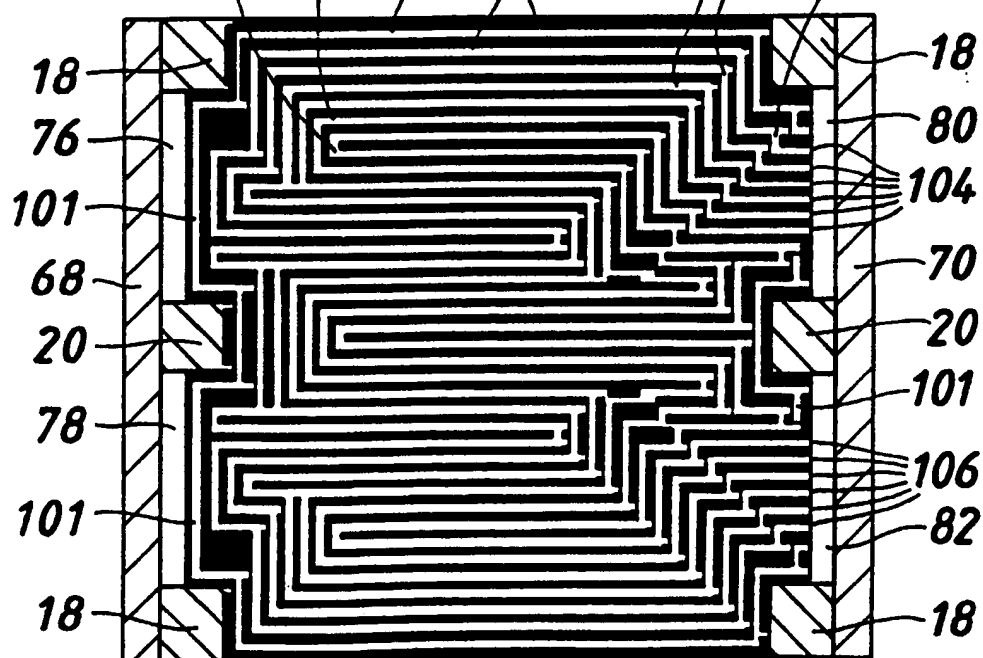


**5/8**

**FIG. 6.**



**FIG. 7.** 113, 111, 109, 102, 100, 107, 105, 103



6/8

FIG. 8.

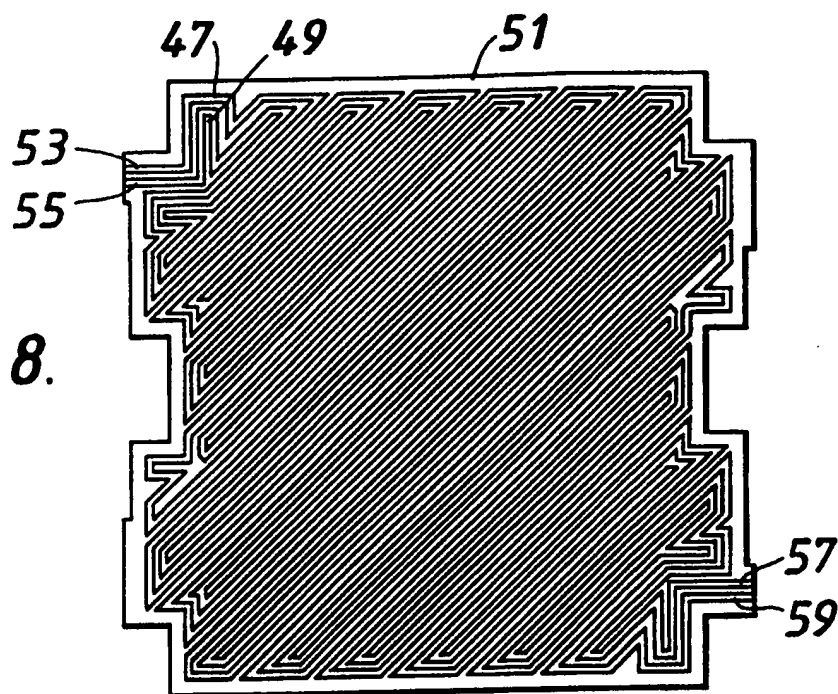


FIG. 9.

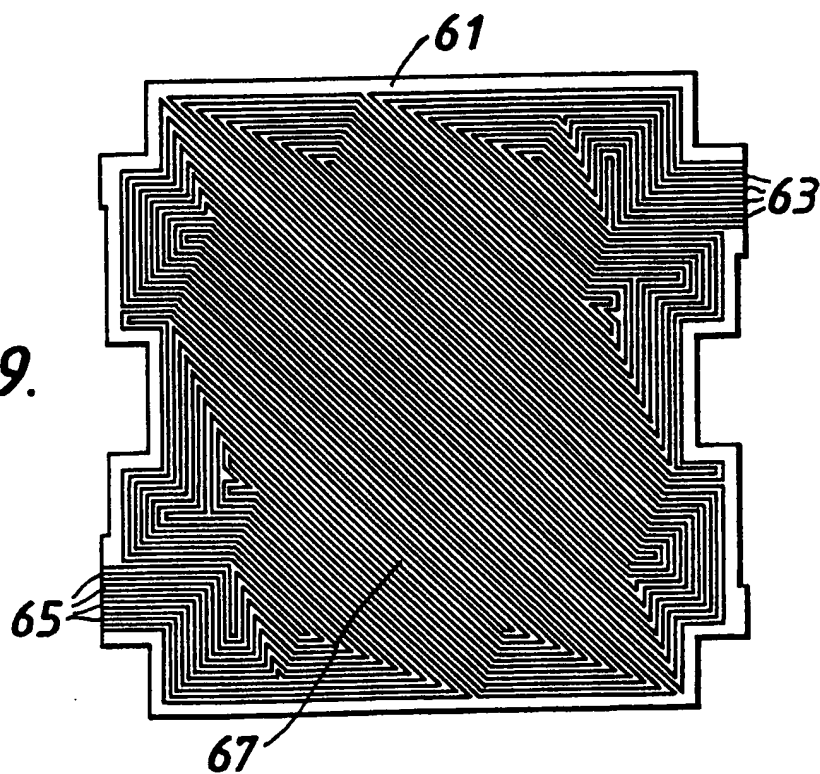


FIG.10.

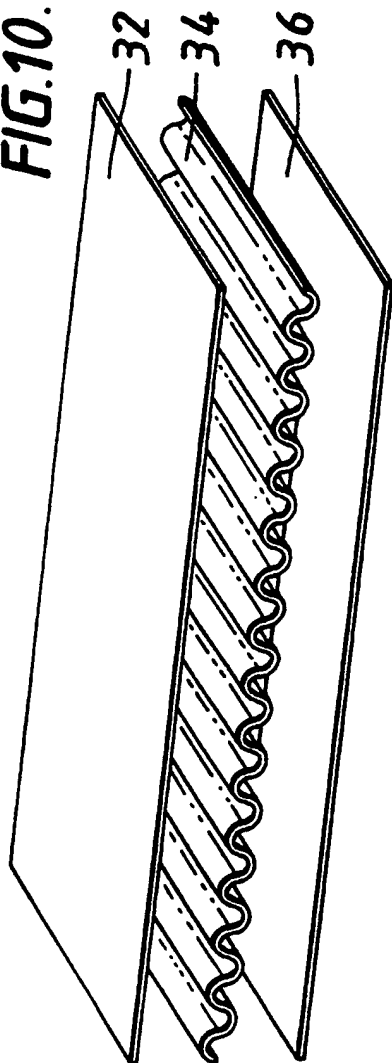
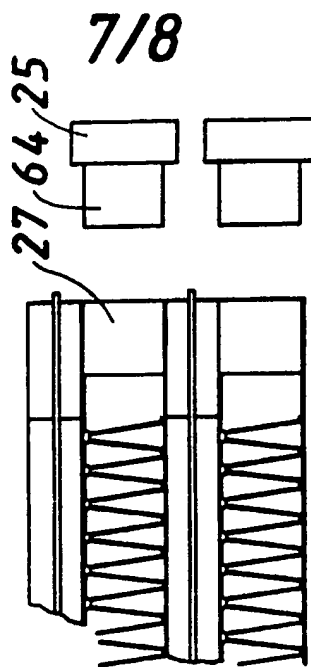
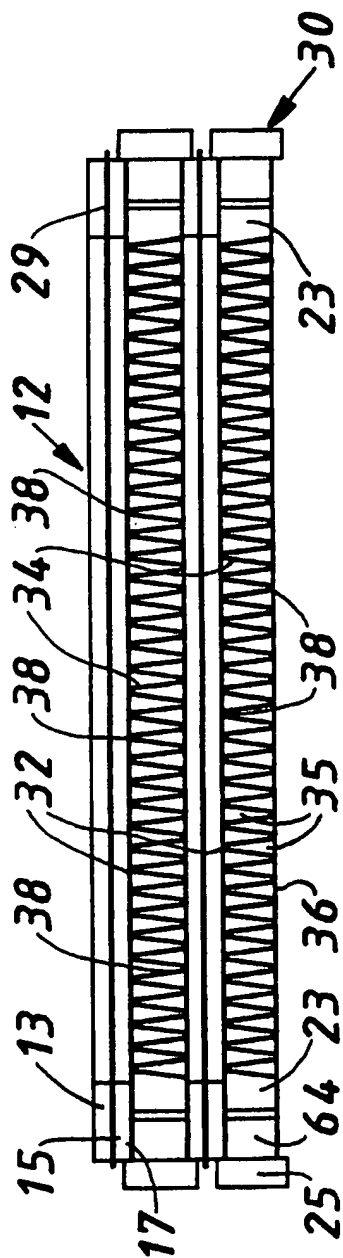


FIG.12.



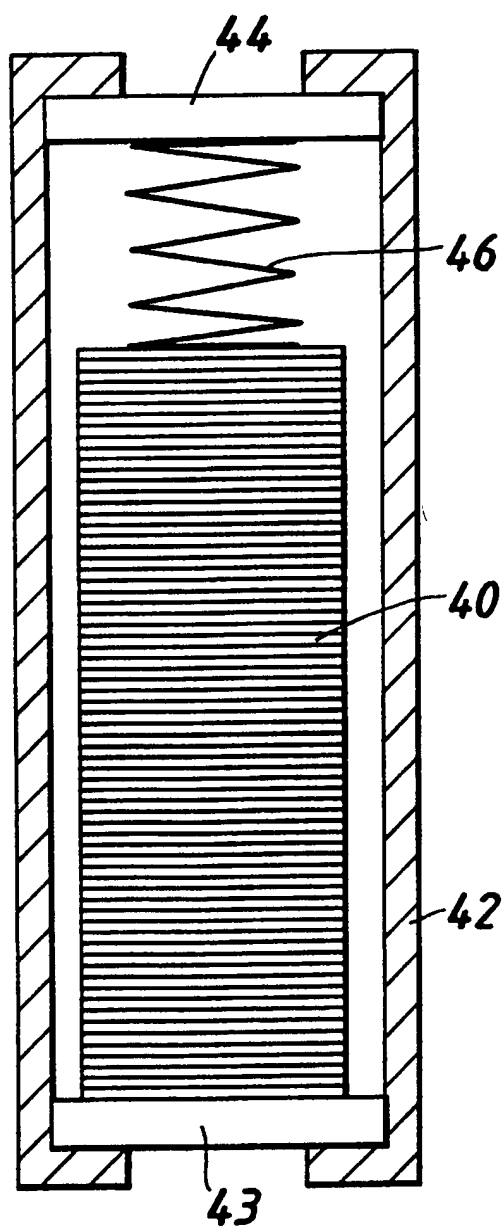
7/8

FIG.11.

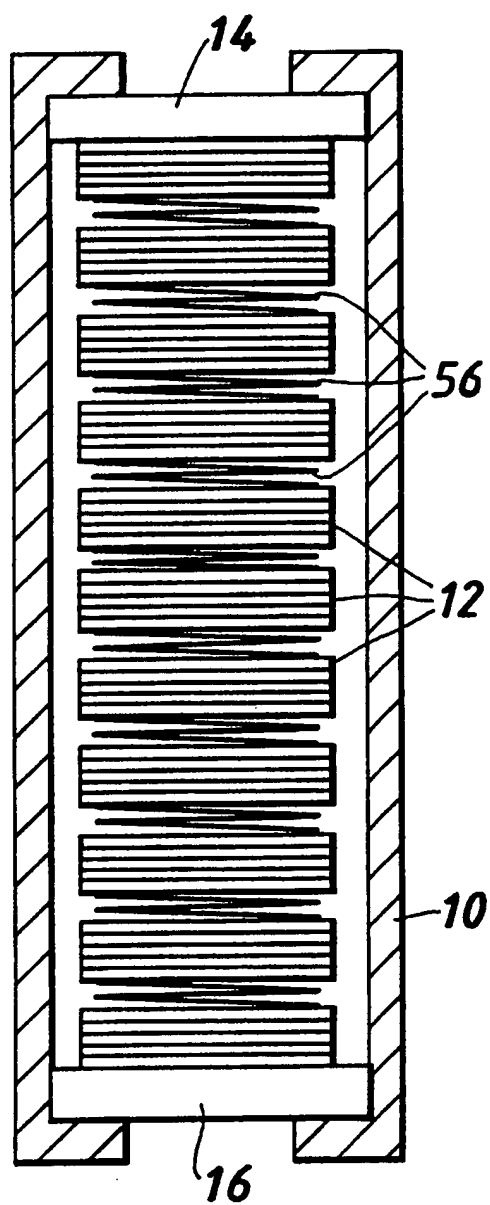


8/8

**FIG.13.**  
**(Prior Art)**



**FIG.14.**



# INTERNATIONAL SEARCH REPORT

Intern. Search No.

PCT/GB 99/01169

**A. CLASSIFICATION OF SUBJECT MATTER**  
IPC 6 H01M8/24 H01M8/04

According to International Patent Classification (IPC), or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

IPC 6 H01M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

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☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

31 August 1999

Date of mailing of the international search report

08/09/1999

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## INTERNATIONAL SEARCH REPORT

Internat. Patent No.

PCT/GB 99/01169

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